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Irrigation Principles and Practices

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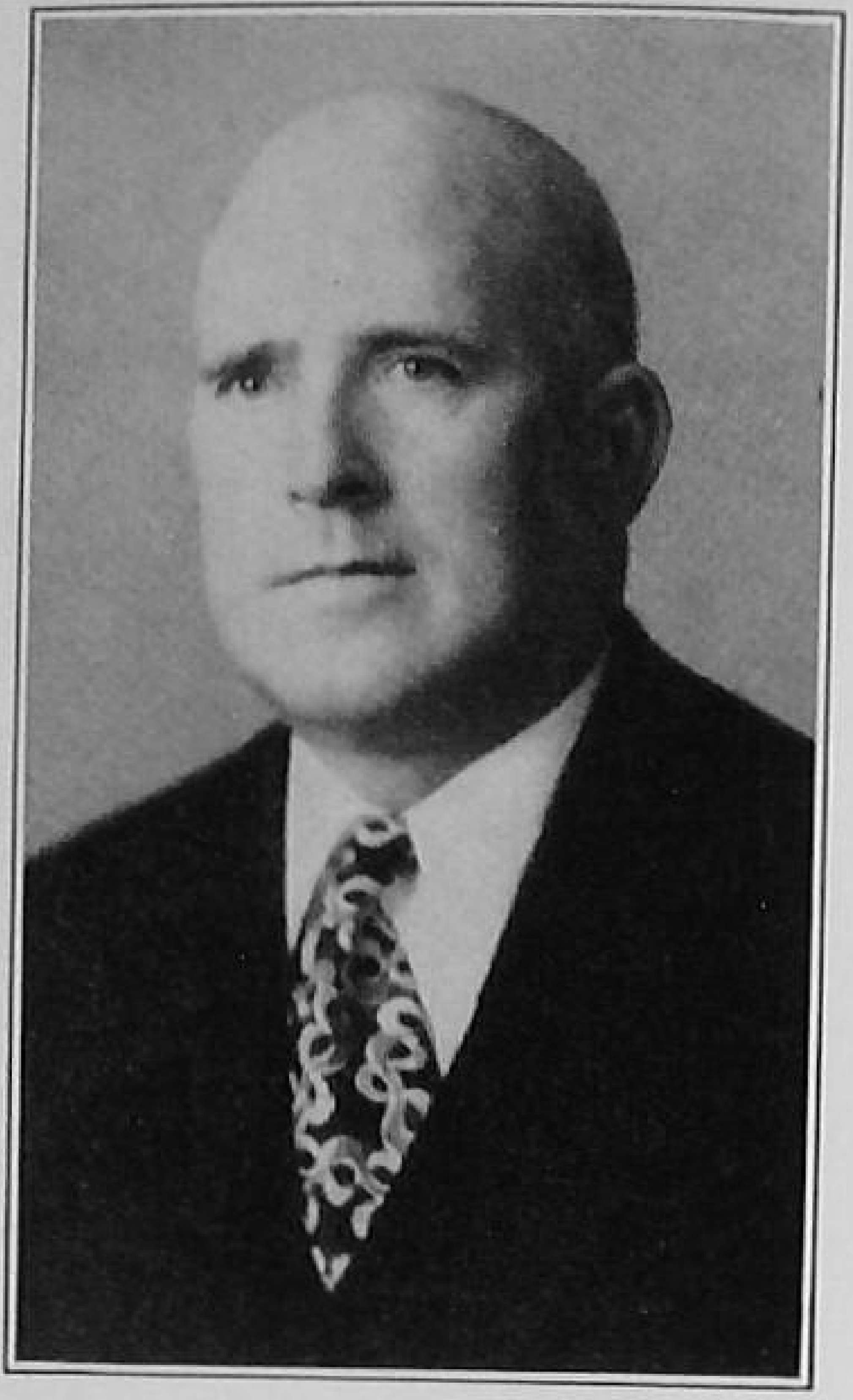

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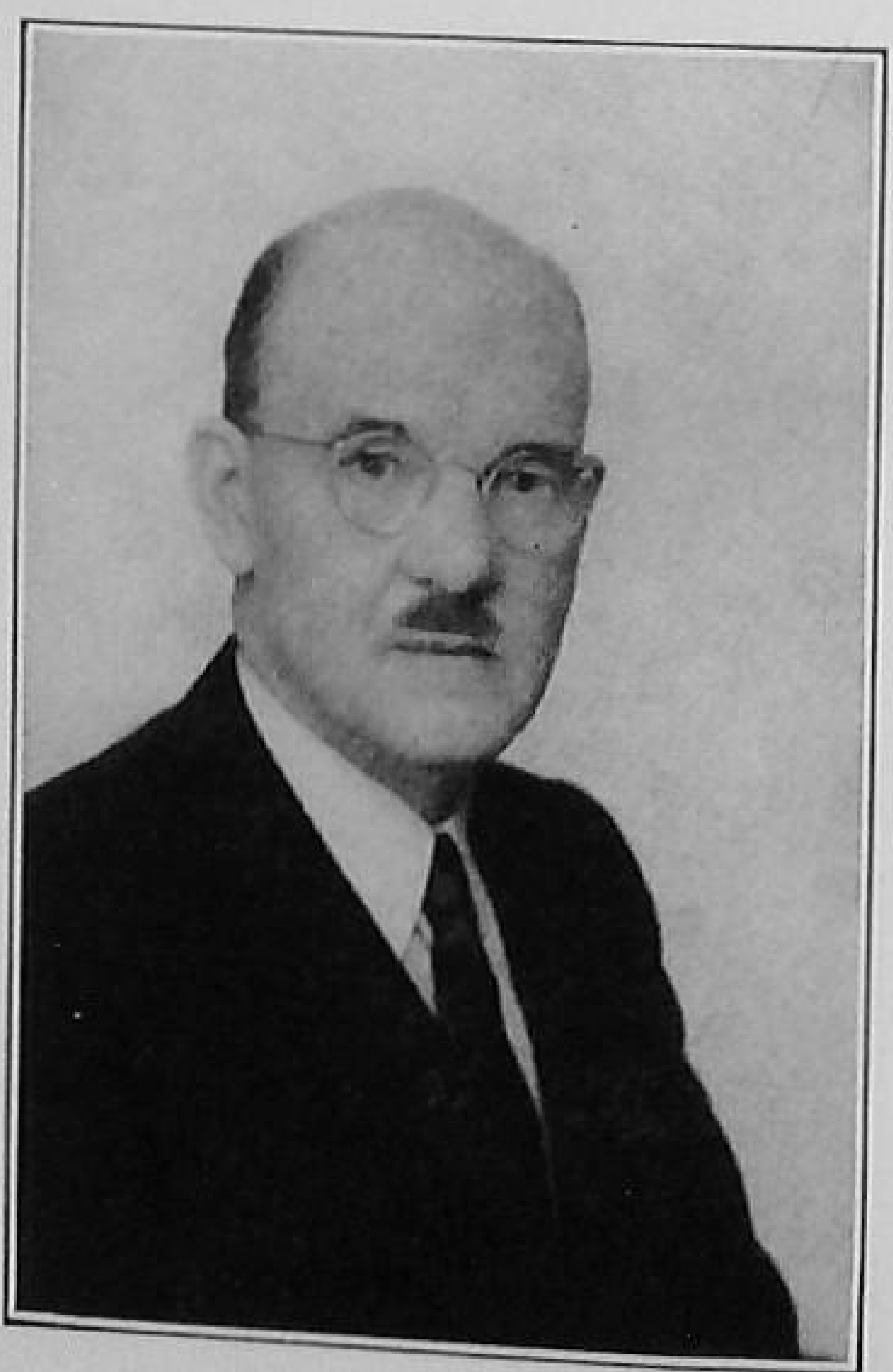

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IRRIGATION SCIENTISTS

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Irrigation Principles and Practices

Second Edition

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THIS BOOK

is dedicated to the research workers whose achievements in the advancement of scientific knowledge of irrigation are becoming increasingly recognized as of basic value toward the perpetuation of a permanently profitable soil productivity under irrigation

Preface

My major objective in the preparation of this book has been to meet the needs of college and university students who seek information concerning the basic aspects of irrigation principles and practices which are of vital importance to the public welfare in arid regions. These aspects of irrigation, sometimes referred to as the agricultural phases, are of special interest to students of agronomy, agricultural engineering, and civil engineering. Although the needs of students have been given first consideration and irrigation principles have been stressed, considerable material describing modern methods and practices is also included. Water commissioners, irrigation company officers, superintendents of irrigation projects, water masters, ditch riders, county agricultural agents in the western states, and irrigation farmers are all interested in the dissemination of knowledge that will contribute to better irrigation practices and more efficient use of irrigation water.

Experience in teaching has convinced me that elementary equations are of value to agricultural and engineering students. It is much easier to establish clearly in the mind of a student who has had a beginners' course in algebra, including the use of logarithms, the influence of canal roughness, cross section, and slope, on the velocity of water and on the discharge of the canal, by means of the equations of Chapters 3 and 4, than by descriptions without the use of symbols and equations. A student who has the mathematics required for college entrance can obtain a clear understanding of most of the equations presented and of the principles that the equations embody. Some aid from instructors in the analysis and use of the equations of Chapters 10 and 12 will be found desirable.

Engineers, agronomists, and soil scientists recognize the need for a study of the physical properties of soils as a basis for intelligent advancement of irrigation practices. Uniform distribution of irrigation water and adequate depth of water penetration into the soil would be much easier to obtain if it were possible for the irrigator to see by simple inspection how deeply into the soil his irrigation water penetrates and to estimate by direct means the depth of water stored in each foot of soil. But, since these things cannot be determined by inspection, they must be determined by indirect means. The equations of Chapter 9 are simple, practical tools which, when used in the light of available information concerning moisture percentages in typical

soils before and after irrigation, enable the irrigator to understand better what becomes of the water he applies.

A study of the flow of water in soils is difficult because of the many variable factors involved. Some simplifying assumptions have been made in the treatment of the topic in Chapter 10.

Decreased use of potentials and potential gradients and the use of more elementary hydraulic terms, particularly hydraulic heads and slopes, and sketches and numerical examples illustrating basic equations of hydraulics have been added to simplify measurements of flow of water in soils. A condensed list of quantities, symbols, units, and force-length-time dimensions is presented to avoid confusion in soil-and-water-relation studies which are basic to progress in irrigation and drainage.

Arid-region peoples have been slow to recognize the necessity for drainage of irrigated lands. My experience, together with recommendations from users of this book, has resulted in the addition of a new chapter on drainage.

Knowledge concerning the consumptive use of water that is very essential to intelligent allotment of water to different areas and regions is presented in Chapter 14 by Harry F. Blaney, a recognized authority.

Chapter 18 on the social and administrative aspects of irrigation, by J. Howard Maughan, will meet an urgent need of students in both humid-climate and arid-climate areas.

Problems and questions to expedite student progress toward understanding Chapters 3 to 14, and to assist teachers, are presented in Appendix A, which also includes questions for Chapter 18. Answers to some of the 140 problems and questions are given. More than 300 selected references to recent publications on irrigation and drainage are presented in Appendix B.

I am grateful to Dean J. E. Christiansen, D. F. Peterson, Jr., C. H. Milligan, and A. A. Bishop of the Utah State Agricultural College; to J. Brownlee Davidson of Iowa State College; to colleagues in the agricultural experiment stations; to C. W. Lauritzen and others of the Division of Irrigation and Water Conservation, Soil Conservation Service; and to collaborators of the United States Regional Salinity Laboratory for their many helpful suggestions.

Ross K. Petersen and E. Arvel Israelsen have assisted in the examination of the publications, and in the preparation of the illustrations and manuscript. O. Allen Israelsen has reviewed and edited the manuscript.

LOGAN, UTAH
June, 1950

ORSON W. ISRAELSEN

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Progress and Problems

Irrigation is an age-old art. Civilizations have risen on irrigated lands; they have also decayed and disintegrated in irrigated regions. In the United States and Canada, irrigation is yet in its youth. Most men who are well informed concerning irrigation are certain of its perpetuity so long as it is intelligently practiced. Others think that a civilization based on agriculture under irrigation is destined sooner or later to decline because some ancient civilizations based on irrigation have declined. The perpetuity of civilized peoples is probably dependent on many factors, of which a permanently profitable agriculture is vitally important. Some of the principles and practices essential to permanently profitable agriculture under irrigation are considered in this volume.

1. Irrigation Defined Irrigation is defined as the artificial application of water to soil for the purpose of supplying the moisture essential to plant growth. Irrigation may be accomplished in different ways: by flooding; by means of furrows, large or small; by applying water underneath the land surface by sub-irrigation and thus causing the ground water to rise; or by sprinkling. In some regions, usually classed as humid, crops are grown satisfactorily every year without irrigation, the necessary soil moisture being supplied by rainfall. In other regions, the rains during some years supply all the water needed by crops, but during other years this source is not adequate. In years of low rainfall, it is economically advantageous in these regions to supply supplemental water by irrigation, the value of the increase in crop yields thus obtained being greater than the cost of irrigation. In regions of very low annual rainfall, and in those where little or no rain falls during the crop-growing season, even though the total annual rainfall is fairly high, irrigation is essential every year in order to produce crops. However, in nearly all areas where irrigation is practiced, crops get some water from the rains, either as moisture stored in the soil from the time of the rainy period to the period of crop growth, or as moisture

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Progress and Problems

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added to the soil directly by the crop-season rains. Irrigation is essentially a practice of supplementing the natural precipitation for the production of crops, and it has the effect of lengthening the growing season.

2. Extent of Irrigation It is estimated that one-third of the earth's surface receives less than 10 in. of water annually and that an additional one-third receives only 10 to 20 in. The United States Bureau of Commerce has listed the geographical distribution of regions of

Irrigated Areas of the World
by Countries, 1948

Country	Millions of Acres Irrigated
Argentina	2.5
Australia	1.0
Brazil	2.0
Canada	1.0
Chile	3.0
China	50.0
Egypt	6.5
France	5.0
French Indo-China	5.0
India and Pakistan	60.0
Iran	2.5
Iraq	3.0
Italy	5.0
Japan	7.5
Java	3.0
Mexico	6.0
Morocco	1.5
Peru	2.0
Philippines	1.0
Russia	8.0
Siam	2.0
Spain	3.5
United States	21.0
Total	202.0
Other countries	3.0
Total	205.0

deficient rainfall as follows: the southwestern parts of Africa, South America, and Australia, the northern part of Africa, the northern and western parts of North America and Asia, and parts of southern Europe. These areas include parts of Canada west of meridian 101, northwestern India up to the Ganges, the greater portion of Australia, Palestine, Iraq, considerable portions of South Africa and adjacent areas, and the Sudan. There are also large semiarid areas in China,

Japan, Turkestan, Egypt, the western United States, Mexico, and countries in South America.

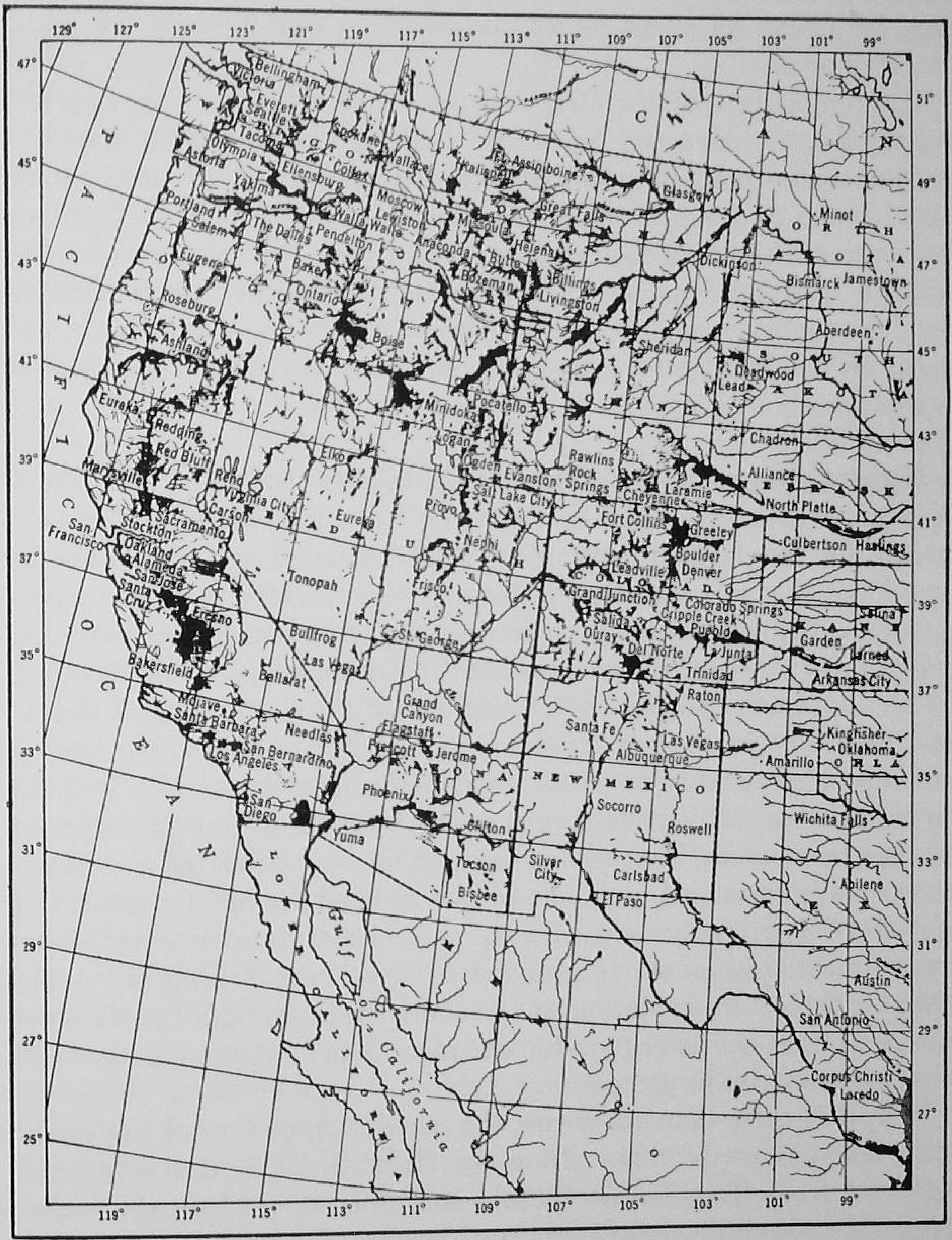

FIG. 1. Map of the Western United States, showing approximate location and extent of irrigated areas. (U.S. Bureau of the Census.)

The United States Bureau of Reclamation has assembled estimates of irrigated areas of the world. A summary showing the extent of irrigation, based largely on these estimates, is given on page 2.

There are more than 200 million acres of irrigated land in the world, of which India and Pakistan have nearly one-third, China one-fourth or more, and the United States one-tenth. Some writers estimate the area for China as about 80 million acres, or one-third of the world irrigated area.

The major part of the irrigated land in North America, approximately 21 million acres, is in the western United States. The approximate location and extent of irrigated lands are shown in the map, Fig. 1, page 3. There is some irrigation in the eastern United States, but because the areas are relatively small they are not shown on the map. In some parts of the eastern United States, the natural rainfall usually supplies enough water to meet all the needs of growing crops. Parts of the West, such as central and southern California, depend almost wholly on irrigation.

3. Present Status of Irrigation in the United States The task of utilizing all the arid-region lands of the United States that may ultimately be irrigated is only about half accomplished. Probably 50 percent of the irrigable area remains non-productive because of lack of water. The capital investment necessary to reclaim the remaining half will far exceed the investment that has been made to supply water for the area now irrigated. The largest reservoirs, the longest canals, and the most expensive tunnels and inverted siphons are yet to be built. The time when these monumental structures will be built for the control of the water supply of the West for irrigation cannot be precisely predicted. The essential fact is that, so long as the population is materially increased each decade, the demand for further utilization of water for irrigation will also increase. The rate of population increase in the western states is especially significant. During the period 1940 to 1947, the population of the seven states on the Pacific slope increased from less than 14 million to more than 18 million, an increase of approximately 30 percent.

In a little more than 100 years, the population of Europe has grown from 200 million to 500 million. In Great Britain, the population increased from 10 million in 1800 to 40 million in 1900. In the United States, the population increased over 70 percent between 1900 and 1940, and between 1930 and 1940, there was an increase of almost 9 million. If the population of the world continues to increase at its present rate, where is the food for these people to come from? The men and women with knowledge of irrigation will be called upon to assist in the solution of this world problem. Desert or arid lands in Arizona, California, Utah, Idaho, and Colorado, which are at present barren because of

lack of moisture, may become highly productive. In Montana, where dry-land farming, particularly wheat raising, is far more extensive than irrigated farming, the State Board of Equalization report shows that an acre of irrigated land is equivalent to 4 acres of non-irrigated, tillable land.

4. Engineering and Agricultural Phases of Irrigation The engineer has the responsibility of designing and building the structures essential to the storage, diversion, conveyance, delivery, and distribution of water to irrigators. It is important that irrigation structures be substantially built so that they may be relied on during critical periods. The failure of a storage dam not only causes the loss of large property investments but sometimes also results in the loss of the lives of many people. The washing-out of a diversion dam or breaking of a canal causes the loss of all or part of the structure and very often the loss of valuable crops by the failure of water when it is needed. Modern irrigation demands that the engineer build structures economically. Some projects are so situated that large quantities of water must be pumped from rivers, lakes, or reservoirs in order to reach the land. The design and installation of suitable pumping machinery are the responsibilities of the engineer. The many outstanding irrigation structures in the world affirm silently but convincingly the skillful achievements of engineers.

A perplexing responsibility confronting the irrigation engineer is the determination of the water needs and supplies for large areas of irrigated land. Reliable predictions of the approximate water yield of a river system from month to month and year to year are based on measurements of rainfall, snowfall, and stream discharges for many years. Unfortunately, the early estimates of water supply were frequently too high and estimates of the water needs too low, with disastrous results to many irrigation projects. Engineers have made remarkable progress toward solving irrigation problems, but the opportunities for advancement are yet very great.

The agricultural phases of irrigation are essentially concerned with the uses of irrigation water on the farm. Many more people are directly concerned with the agricultural than with the engineering phases. Every irrigation farmer must decide important questions concerning his irrigation practice, and some of these questions have to be decided each year—they cannot be decided once for all time. There are no specific rules applicable to all arid-region climates, to all soils, and for all crops, as to when irrigation water should be applied to the soil. The seasonal depths of irrigation water required to produce crops

economically under different climatic and soil conditions perplex many irrigation farmers.

Agricultural aspects of irrigation include the determination of the proper depths of water necessary in single applications, how to distribute the water uniformly, the capacities of different soils for irrigation water, and the flow of water in soils.

In order to make the most efficient use of water, the methods and practices in irrigation must be based on the climatic and soil conditions provided by nature in the locality concerned. The crops grown are selected to some extent according to the climatic conditions under which the farmer works. Agricultural engineers and agronomists have the opportunity and the responsibility of finding the necessary facts with which to aid the irrigator and answer correctly the many perplexing questions in the agricultural aspects of irrigation.

5. Climate and Irrigation The snow, rain, wind, humidity, temperature, sunshine, and length of growing season all influence irrigation practices. In some localities, such as parts of Arizona, California, New Mexico, and western Texas, irrigation is practiced from 10 to 12 mo. of every year and is essential to satisfactory crop production. In other places, like parts of Montana and Canada, the rainfall during some years is so abundant that irrigation is of doubtful value. *Irrigation is fundamentally a practice of supplementing that part of the natural precipitation which is available for crop production.* The amount of water used in irrigation practice varies from place to place and from time to time as the natural precipitation varies. There are a few arid valleys in which the natural precipitation is so small that it is of negligible value in crop growth. As a general rule the moisture made available by nature should be carefully conserved for the use of plants and should be considered in estimating the irrigation needs of soils and crops.

6. Soils and Irrigation The influences of soil properties on irrigation practice are of very great importance. As a rule the importance of soil influences on irrigation practice is underestimated. Some soils consist of coarse particles loosely compacted, and these are highly permeable to water. Others consist of fine particles tightly compacted, and these are almost impermeable to water. Research shows that some soils transmit water several thousand times faster than other soils. The permeability of a soil greatly influences irrigation practice. Highly permeable soils tend to cause excessive water losses through deep percolation, whereas impermeable soils are difficult to moisten adequately. Soils are also storage reservoirs in which irrigation water is held be-

tween the periods of irrigation for the use of plants. The size of soil particles, their compactness, the depth of the soil, the organic matter it contains, and the position of the water table—all these soil properties influence the depth of available water that the irrigator can store in his root-zone soil in a single irrigation and hence influence the required frequency of irrigation. The depth of the soil greatly influences its capacity as a storage reservoir for water and the necessary frequency of irrigation. *Variation* in size of soil particles, compactness, permeability, and depth from place to place is the rule and not the exception. There is no such thing as uniformity in *natural* soils. The irrigation farmer finds it essential to study his soil carefully in order to make his irrigation practices conform to the conditions of the soil on which he desires to produce crops profitably.

The irrigation farmer whose good fortune it is to be located on highly productive soils with an adequate supply of irrigation water is usually successful in making a good living and meeting his irrigation expenses. The farmer whose ill fortune it is to be located on poorly productive soils is unable either to make a good living or to meet his expenses. The productivity of the soil is often decreased from year to year because of the gradual rise of the ground water followed by salinity and alkali problems.

To assure a permanently profitable agriculture, the irrigation farmer must intelligently consider the problems of soil maintenance, even with the best arid-region soils. The experiences of farmers in the irrigated sections of the United States seem to have established the fact that, to maintain a high productive capacity of soils, it is essential to apply barnyard manure, plow under green-manure crops, and use other fertilizers.

2

Sources and Storage of Irrigation Water

Rain and snow constitute the primary sources of water for irrigation. As a rule, the precipitation which falls on the valley lands in irrigated regions is of comparatively little consequence as a source of water; that which falls on the mountain areas is the chief source of supply. The success of every irrigation project rests largely on the adequacy and dependability of its water supply. In irrigated regions public agencies should make continuous long-time records of precipitation and stream flow and ground-water storage as a basis for intelligent and complete utilization of all water resources.

7. Precipitation and Temperature Water and heat are essential to the growth of all crops. In irrigated regions these two essentials are provided by nature at different time periods. In general, most precipitation occurs during cold, non-crop-growing months and least precipitation occurs in the frost-free months during which crop growth occurs. In some irrigated valleys, notably in Nevada and California, the precipitation is so small during the season of most rapid plant growth that it moistens only the surface soil and is soon evaporated. The fact that the precipitation is low during the months of highest mean temperatures is illustrated in Fig. 2, which reports average precipitation together with average, low, mean, and high temperatures for each month at certain towns in Utah, Oregon, Nevada, and California.

8. Annual Precipitation Regions that annually receive large amounts of precipitation are known as humid; those that get small amounts each year are considered semi-arid or arid. The annual precipitation on the surface of the earth varies widely—from zero inches in desert regions such as Aswan, Egypt, to 600 inches or more at Assam, India. Where the annual precipitation is 30 inches or more, irrigation may not be essential to the growth of crops. However, in some localities, such as parts of the Hawaiian Islands, irrigation is profitable in spite of

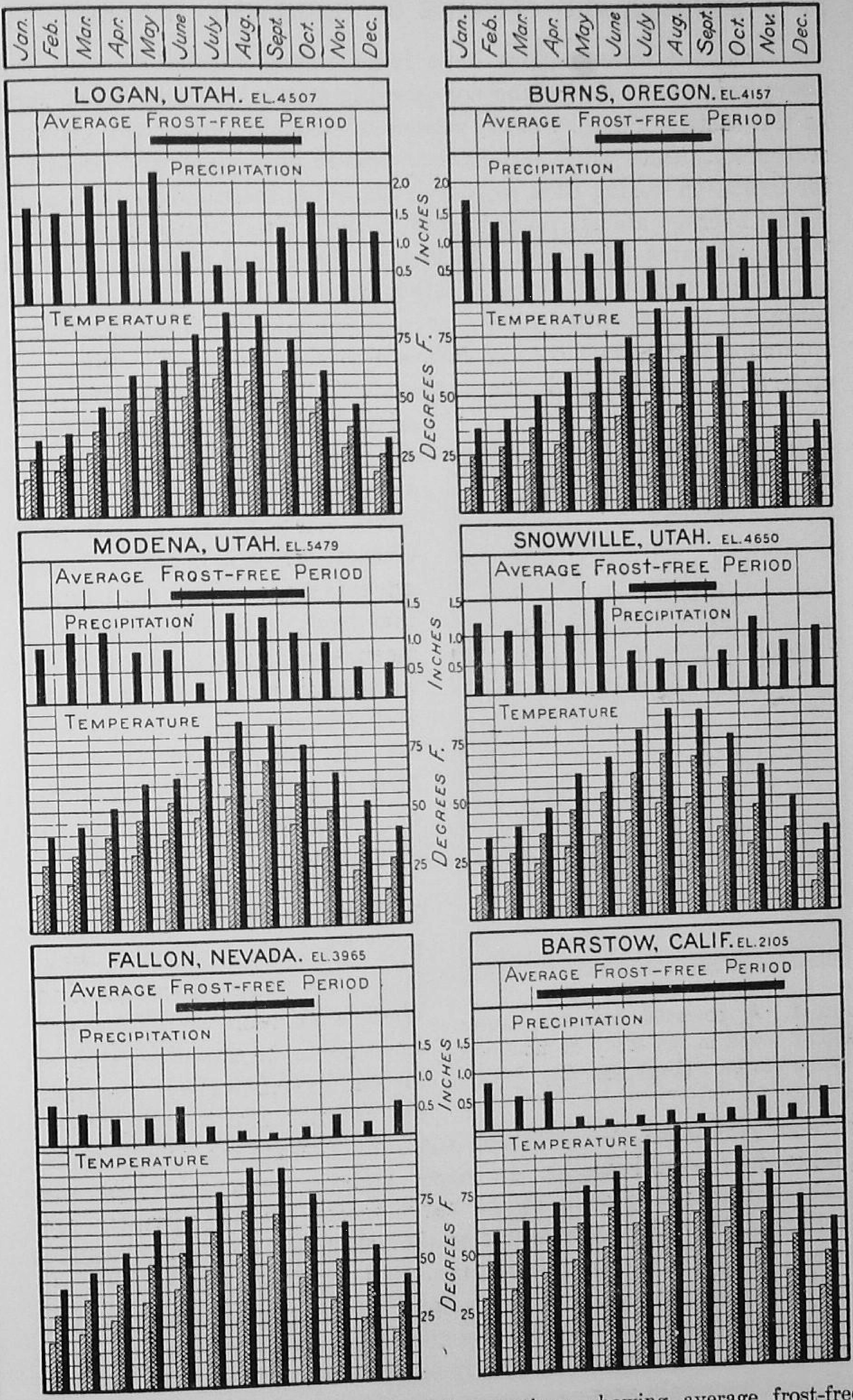

FIG. 2. Condensed climatology of typical stations, showing average frost-free period; mean monthly precipitation; and mean minimum (lightly shaded bars), mean (double shaded bars), and maximum (solid bars) temperatures.

the fact that these regions have large annual rainfall because the heavy rains come during the non-growing season. In other areas, such as the eastern United States, periods of drought during the growing season sometimes cause serious decreases in crop yield, and provision for irrigation during such periods is becoming increasingly profitable.

The average annual precipitation in the United States is shown in Fig. 3, prepared from data collected by the United States Geological Survey and the United States Weather Bureau. The map shows that in going east from meridian 101 the average annual rainfall increases from approximately 20 inches to 35 inches near the Great Lake states and up to 50 inches or more in the southeastern states. In the eastern parts of the Dakotas, Nebraska, Kansas, Oklahoma, and Texas, irrigation is essential only during the dry years, whereas in the western parts of these states it is nearly always advantageous. The map shows that great variability exists in the mean annual precipitation of the western states. However, all the arable lands lying west of meridian 101, except parts of western Montana, Oregon, and Washington, are usually benefited by irrigation.

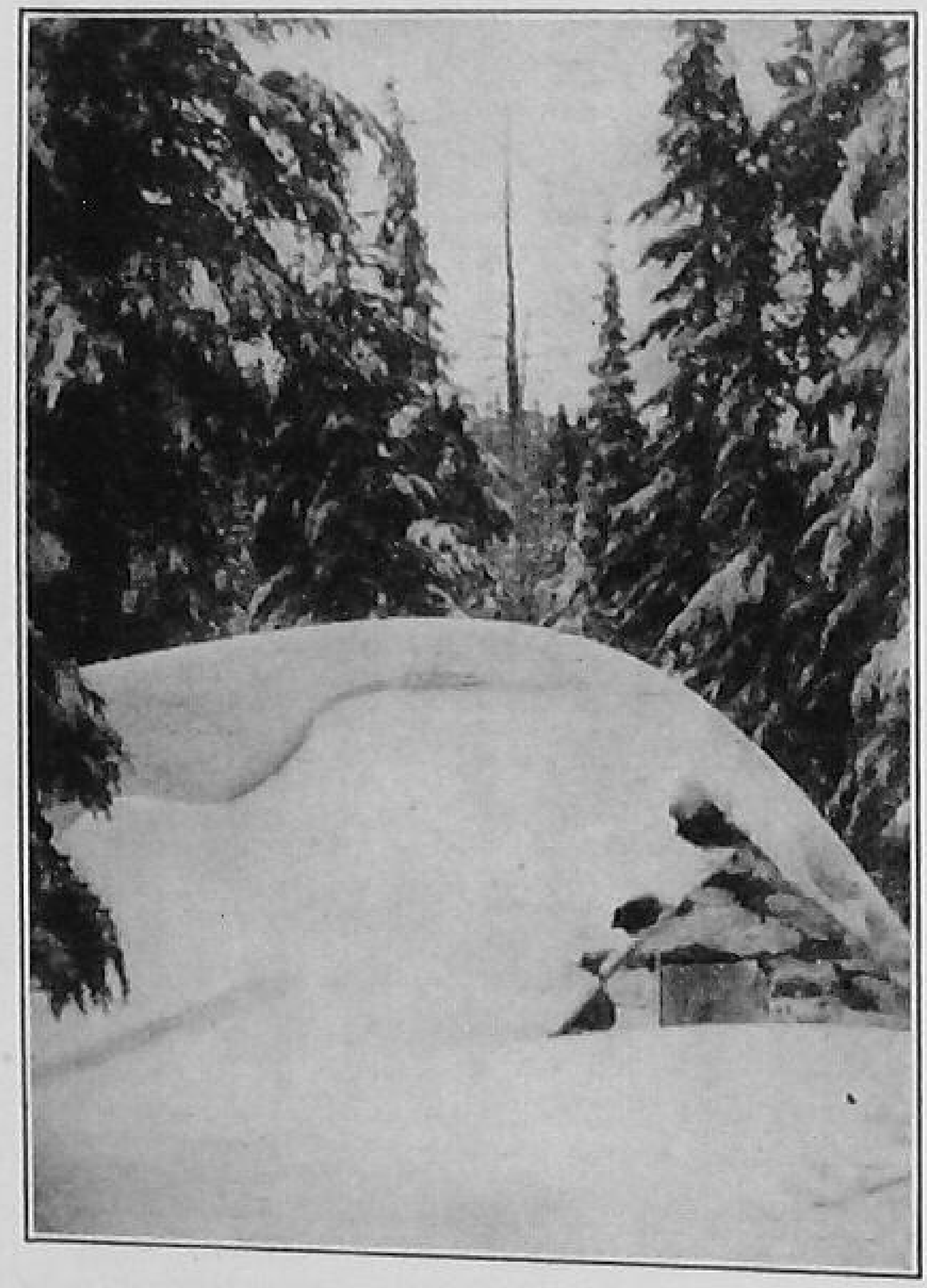

FIG. 4. A potential irrigation water supply found in the study of mountain snow covers. (Utah Agr. Exp. Sta.)

9. Valley and Mountain Precipitation The rain and snow which falls in the irrigated valleys of the West is valuable as a source of moisture to be stored directly in the soil. In some valleys the winter precipitation stores enough moisture to germinate the seeds and maintain the growth of the young plants for several weeks. In these valleys, perennial crops also make substantial growth in the early season by using winter precipitation which has been stored in the soil. Other arid-region valleys receive so little winter precipitation that farmers must irrigate the soil before seeding their crops in order to insure a sufficient amount of moisture to germinate the seeds and start satisfactory growth. Such valleys must depend almost wholly on the rain and snow that falls in adjacent mountain areas as a source of their supply of water for irriga-

MAP OF UNITED STATES SHOWING MEAN ANNUAL PRECIPITATION

Red lines and figures indicate average annual precipitation in depth in inches

Prepared by Henry Gannett
mainly from data of the
United States Geological Survey
and United States Weather Bureau

By courtesy U. S. Geological Survey

Fig. 3.

tion. As a rule, in nearly all irrigated regions, the valley precipitation is relatively unimportant as a direct source of irrigation water. The precipitation in the mountain areas, as illustrated in Fig. 4, constitutes a major source of water supply. This condition presents to the people of arid regions very interesting and yet perplexing problems in the conveyance of water from the mountainous sources to the valley lands. It also gives rise to an urgent need for painstaking study of the seasonal and annual water yield of each mountainous area on which the rain and snow fall. The vital problems which demand intelligent solution as a basis for complete and economical utilization of nearly all western natural resources are inseparably connected with the water yield of a watershed, its conveyance to places of use, and its economical use, whether for power, irrigation, or domestic or industrial purposes. The purpose of this volume is primarily to promote information essential to the economical use of water in irrigation. However, there is urgent need for a wider recognition of the fact that intelligent solution of watershed-yield problems and of economical conveyance of water will appreciably advance the general welfare.

10. Water-Supply Studies The accumulation of dependable information concerning water supply demands intelligent and painstaking endeavor and continuous effort. It is probable that inadequate water supply has contributed most to the years of financial stress and ultimate failure of many irrigation projects. Over-optimism and conclusions based on insufficient knowledge of watershed yield have been common and expensive follies among many leading western citizens in both private and public places. Overestimates of water supply for various projects are frequently reflected in the small areas of land actually irrigated as compared to the area of land irrigated in the original project. These overestimates have been made largely during cycles of "wet" years and have been followed by disastrous results during cycles of "dry" years. The occurrence of these climatic cycles, which cannot as yet be predicted with precision, together with the wide variations of precipitation and stream flow from one time of year to another, complicates the problem of economically using all the available water every year. Yet arid-region communities may intelligently adjust their irrigation practices, to some extent, on the basis of reliable information concerning water supplies. This information is based on the measurement of water content of snow covers such as illustrated in Fig. 5. To outline the nature of, and the procedure in, the necessary water-supply investigations is beyond the scope of this book. It is urgent that public officials be advised as to the vital im-

portance of the problem, and that public funds be made available in sufficient amounts to prosecute thorough investigations on every stream system concerning the watershed yield and the supply of water for further irrigation expansion.

Fig. 5. Measurement of water content of snow covers. (Courtesy Soil Conservation Service.)

11. Natural Streams During the early development of modern irrigation in America, natural stream flow supplied all the water that was needed for irrigation. The discharge of most natural streams decreases greatly during the late summer months when the largest supply of water is needed for irrigation. This fact is illustrated by Fig. 6, which gives the monthly discharge of three typical rivers in the Great Basin. The mean monthly discharge of Logan River (Utah) for August is only 12,000 acre-feet as compared to 48,000 acre-feet in June. The average annual discharge, based on a 34-year period, is 228,000 acre-feet.

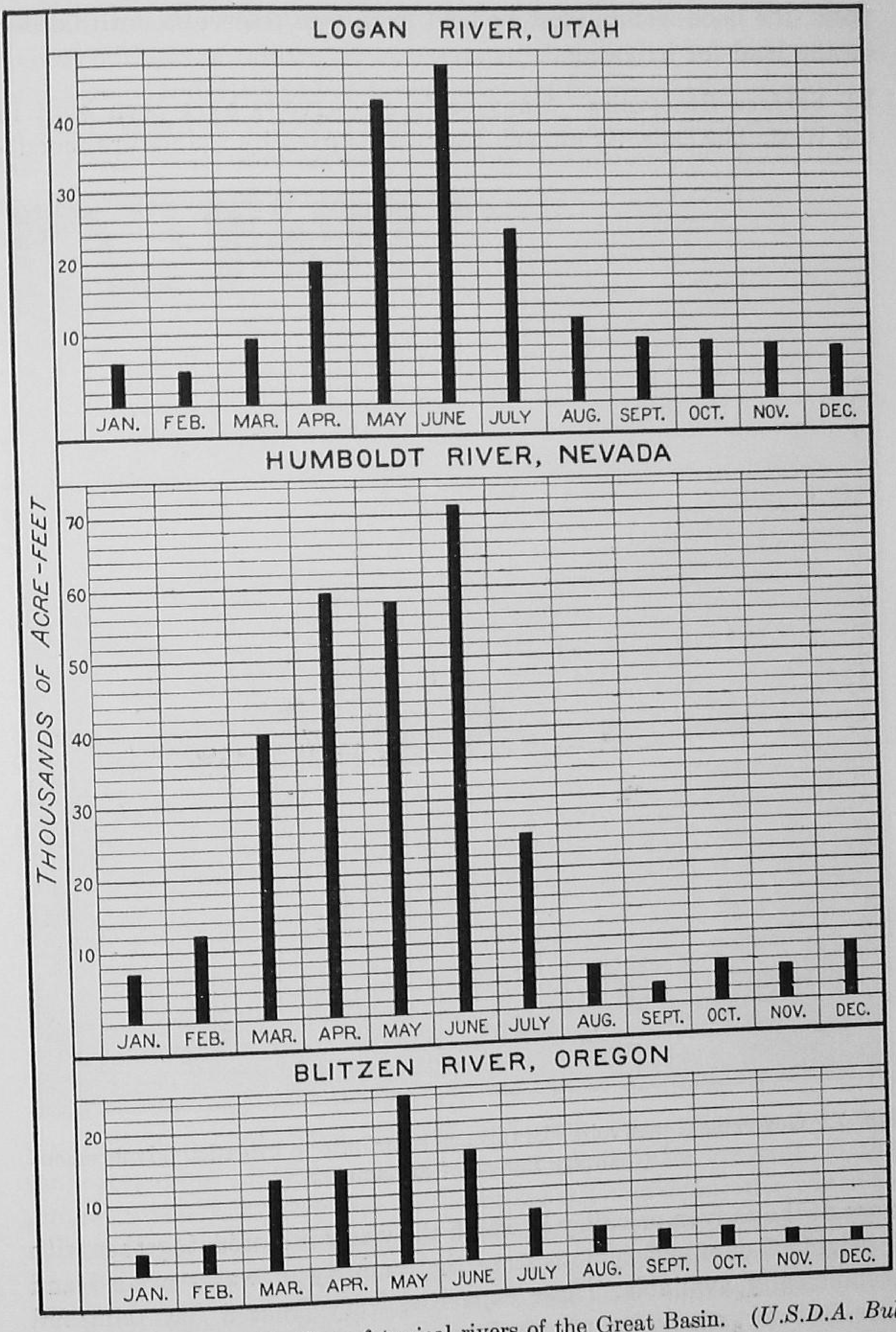

FIG. 6. Mean monthly flow of typical rivers of the Great Basin. (*U.S.D.A. Bul.* 1340.)

In order to use all the water of western streams for irrigation purposes, the flood waters must be held in storage reservoirs until needed on the land for irrigation.

12. Surface Reservoirs Many surface reservoirs have been built in the West. The capacity of each reservoir is fixed by the natural condi-

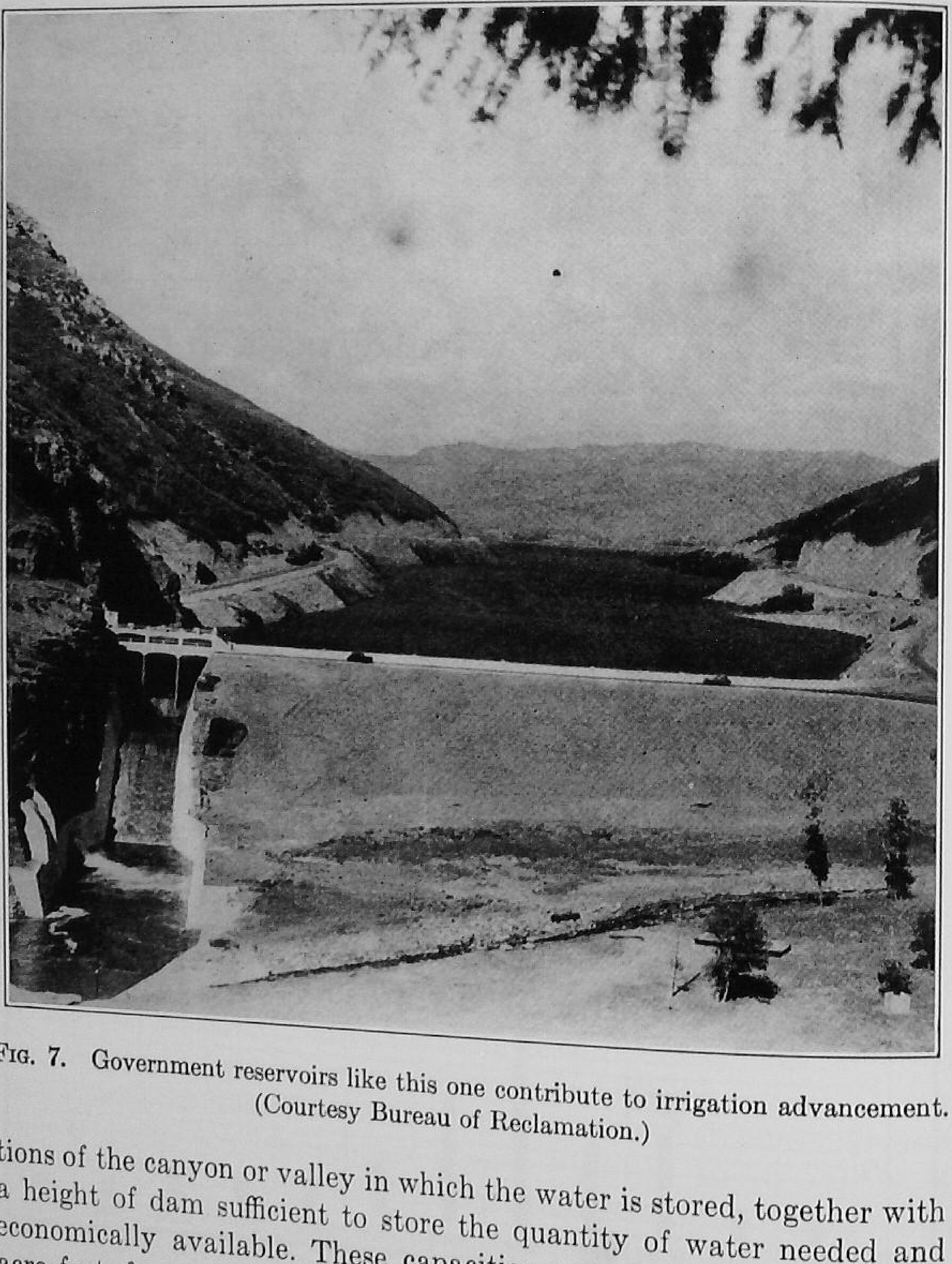

FIG. 7. Government reservoirs like this one contribute to irrigation advancement. (Courtesy Bureau of Reclamation.)

tions of the canyon or valley in which the water is stored, together with a height of dam sufficient to store the quantity of water needed and economically available. These capacities vary from a few thousand acre-feet for reservoirs on small streams, as shown in Fig. 7, to more than 32 million acre-feet for one of the U. S. Government's new reservoirs, shown in Fig. 8. Likewise, the dams constructed for irriga-

tion purposes vary from a few feet in height, built at a low cost, to massive masonry structures over 700 feet high and built at a cost of several millions of dollars. It is estimated that nearly one-half of the total annual water supply of the West is yet to be used for irrigation. Of the one-half now used, probably 40 to 50 million acre-feet is obtained each year from storage reservoirs. Ultimately, when the total annual water supply of the West is applied to some 40 million acres of irrigated land, probably two-thirds or more of the supply will each year be obtained directly from storage reservoirs. Provision of the additional water-storage capacity will necessitate the construction of higher and more expensive dams than have thus far been built. The time at which these structures will be needed is dependent largely on the increase in demand for food products.

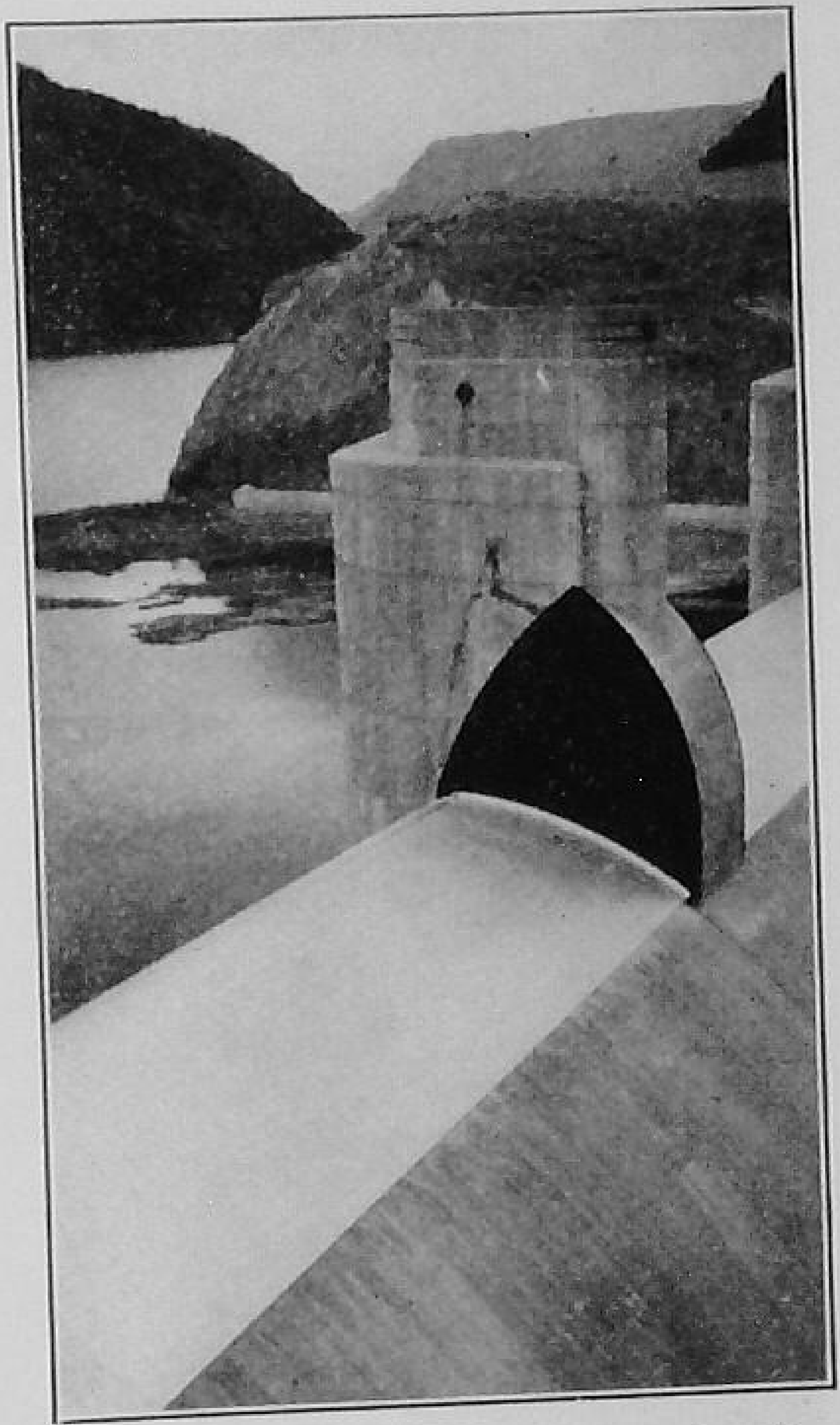

FIG. 8. The Boulder Dam showing spillway crest on Arizona side and Lake Mead Reservoir in the background. (Photograph by author, 1939.)

13. Underground Reservoirs In parts of Arizona, California, and other western states, large volumes of water occur in saturated coarse gravels well beneath the valley land surface. Pumping water from underground sources is widely practiced and is a well-established method of obtaining irrigation water. The lowering of the ground-water table which has followed extensive pumping for irrigation in some places has proved valuable as a means of drainage. In other localities the ground-water surface has been lowered so much by irrigation pumping that deepening of wells has become necessary. The lowering of the ground water has increased the pumping lift and made the water so obtained increasingly expensive. Reasonable lowering of the ground-water surface each year, in a locality where conditions are favorable for pumping, develops capacity for subsequent underground water storage.

Systematic flooding of land surfaces overlying or draining into underground reservoirs is becoming a recognized method of water storage.

FIG. 9. Aerial view of San Antonio Creek debris fan with snow-covered Mount San Antonio in background. In the foreground, to the right of the diagonal light streak that marks the course of the stream, the white strips extending from left to right represent rock dams which form terraced basins and hold the storm water. (*U.S.D.A. Tech. Bul.* 578.)

In areas dependent on pumped water for irrigation, or for other purposes, the underground water supply can be increased by artificial methods of recharging. This fact has been adequately demonstrated in several western states, particularly in Arizona, California, and Texas. A typical canyon debris fan with rock dams to retard flood flow in terraced basins causing infiltration to recharge a California ground-water basin is shown in Fig. 9.

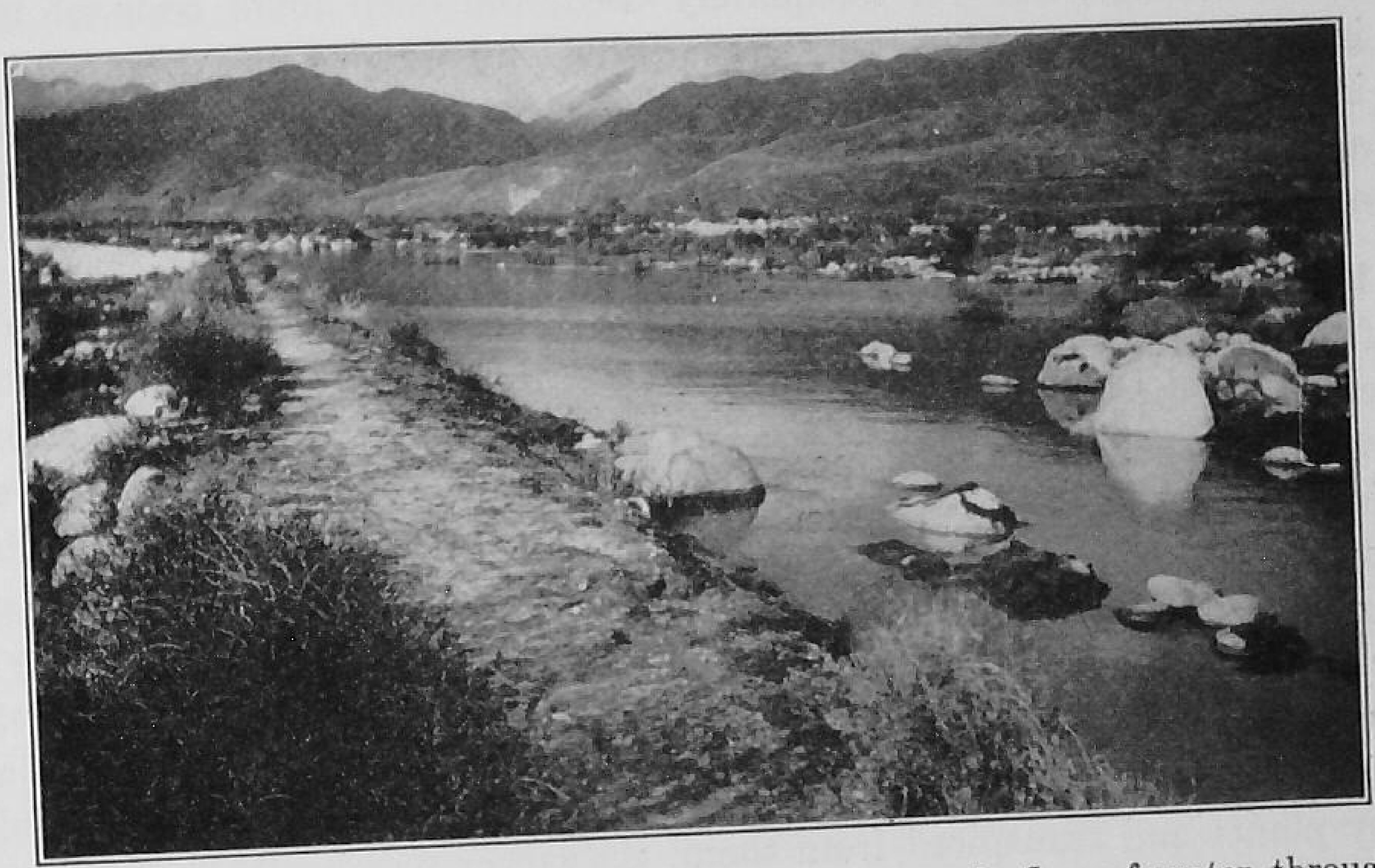

FIG. 10. Soil placed against upper face of dikes retards flow of water through them and encourages ponding of water from crest of lower dike to toe of dike next above. (*U.S.D.A. Tech. Bul.* 578.)

Rock dams, or dikes, with soil on the upstream face, form ponds like the one shown in Fig. 10, from which the water percolates into the ground-water reservoir to be stored until needed for irrigation during the months of pumping.

To a limited extent the gravels under the higher lands may serve as ground-water reservoirs, provided that the flow of the ground water toward the lower levels is not too rapid. The question of the advisability of spreading water over land surfaces during the periods of surplus flow as a means of storing it for later use is one for which there is no general answer. Local conditions determine the capacity of the ground-water storage, the method, the percentage, the cost of water recovery, and the feasibility of equitably distributing the water stored by different irrigation interests. These and other, more detailed problems demand attention in each locality as a basis for determining the advisability of such storage.

14. Soil Root Zone Reservoirs The soil root zone in arid regions varies from 2 to 6 feet or more in depth. Loam soils, for example, may well average 5 feet depth and provide considerable storage capacity for capillary water that may be absorbed by plant roots. As shown in Chapter 9, the storage capacity of unsaturated soils for water in a form available to plants ranges from 1 inch per foot depth of soil up to 2 inches or more. To illustrate the importance of this capillary soil water storage, not yet adequately used, the deep loam soils of the irrigated lands on which winter precipitation is inadequate, if carefully irrigated during the fall or winter months, may store millions of acre-feet of water for use by plants during the early crop-growing season.

15. Irrigation Efficiencies The desired attainment in diverting water from natural sources for irrigation purposes is to produce the maximum crops consistent with economic conditions. As a general rule, reduction of wastes, and consequent increase in effective use of natural resources, including irrigation water, results in *economical* use, provided the costs of reducing wastes are not excessive. Irrigation efficiencies can be increased by reducing the losses of water in conveyance, delivery, runoff, deep percolation, and evaporation. With a given quantity of water diverted from a river, the larger the proportion that is stored in the root-zone soil of the irrigated farms and there held until absorbed by plants and transpired from them, the larger will be the total crop yield. The expression *irrigation efficiency* is here defined as the ratio of the water consumed by the crops of an irrigation farm or project to the water diverted from a river or other natural water source into the farm or project canal or canals.

Let E_i = irrigation efficiency, percent.
W_c = the *irrigation* water *consumed* by the crops of an irrigation farm or project during their growth period.
W_f = the water delivered to the farms of a project during a given period of time.
W_r = the water *diverted* from a river or other natural source into the farm or project canals during the same period of time.
W_s = the water stored in the root-zone soil.

Then

$$E_i = \frac{100W_c}{W_r} \tag{1}$$

The irrigation efficiency percentage is influenced by the water conveyance and delivery efficiency and the water application efficiency. When

these efficiencies are increased, irrigation efficiencies also are increased. In most irrigated regions, the irrigation efficiency may be substantially increased to the economic advantage of the communities concerned. Because of the many sources of loss of irrigation water between the time and place it is diverted from rivers, and the time and place where it is stored in the root-zone soil as water readily available to plants, the irrigation efficiency on most projects is low, probably less than 33 percent.

Suppose, as an example of comparatively good irrigation practice, that 40 percent of the water diverted is lost in conveyance and delivery; 30 percent of the water delivered to the farms, W_f, is lost as surface runoff and deep percolation; 20 percent of the water stored in the soil, W_s, is lost by evaporation. Then it follows that:

$$W_f = 0.6W_r$$

$$W_s = 0.7W_f = 0.42W_r$$

$$W_c = 0.8W_s = 0.34W_r$$

and

$$E_i = \frac{100W_c}{W_r} = 34 \text{ percent}$$

As an example of rather poor irrigation practice, consider that 60 percent of the water diverted is lost in conveyance and delivery, 50 percent of the water delivered is lost as surface runoff and deep percolation, 40 percent of the water stored in the soil is lost by evaporation; then:

$$W_f = 0.4W_r$$

$$W_s = 0.5W_f = 0.2W_r$$

$$W_c = 0.6W_s = 0.12W_r$$

and

$$E_i = \frac{100W_c}{W_r} = 12 \text{ percent}$$

If these estimates are even approximately correct, indicating that less than one-third of the water diverted for irrigation is consumed by growing crops, it is apparent that serious consideration should be given to increasing irrigation efficiencies.

3

Measurement of Irrigation Water

The efficient use of water for irrigation depends largely on measurement of water. Increasing utilization and value of available water, and the growing tendency among irrigation companies to base annual water charges on the water used, make an understanding of the principles and methods of water measurement necessary. Information concerning the relations of water, soils, and plants cannot be utilized in irrigation practice without the measurement of water.

To facilitate student progress toward obtaining a clear understanding of quantities considered, symbols used, units employed, and the basic physical properties of equations presented in the text, a quantity reference table is presented and referred to in Chapters 3 to 12.

This table is designated Table QR. Its usefulness is explained in connection with the presentation and discussion of equations. This table includes 38 items and 78 quantities. Closely related quantities are grouped and presented under one item. For example, item 7 includes 5 quantities. Some of the symbols, such as d and h, represent several different quantities and thus avoid *excessive use* of subscripts.

16. Units of Water Measurement The units of water measurement are considered in two classes: first, those expressing a specific volume of water at rest; and second, those expressing a time rate of flow. The commonly used units of volume of water at rest are the gallon, cubic foot, acre-inch, and acre-foot. An acre-inch is a volume of water sufficient to cover 1 acre 1 in. deep, which is 3630 cu ft. An acre-foot of water will cover 1 acre 1 ft deep, and is equal to 43,560 cu ft.

The commonly used units of rate of flow are gallons per minute, cubic feet per second, acre-inches per hour, and acre-feet per day. The miner's inch is also used. It is defined as the quantity of water that will flow through an opening 1 in. square in a vertical wall under a pressure head ranging from 4 to 7 in. Each of the western states defines the miner's inch in terms of 1 cu ft per sec. One miner's inch is

TABLE QR

REFERENCE LIST OF WATER MEASUREMENT, CONVEYANCE, SOIL-WATER RELATION, AND EFFICIENCY QUANTITIES, WITH AMERICAN UNITS AND FORCE-LENGTH-TIME DIMENSIONS*

Item	Quantity	Symbols	American Engineering Units	Force-Length-Time Dimensions
				F-L-T
1	Areas in irrigation and drainage:			
	a. Section of stream of water at right angles to flow	a	sq ft	L^2
	b. Soil through which water flows	a	sq ft	L^2
	c. Land covered with water at any time, t, while irrigating a border strip	A	acres	L^2
2	Atmospheric pressure:			
	a. As pressure intensity	p	psi	F/L^2
	b. As a pressure head	h_p	ft water or in. mercury	L
3	Bed width of an irrigation canal, or open drain	b	ft	L
4	Circle of influence in ground-water pumping, radius of. Also one-half spacing of drains	R	ft	L
5	Coefficients of discharge (differences in usage are indicated by use of the prime, C', C'', etc.) for orifices and weirs	C	......	$L^{1/2}/T$
6	Coefficient of roughness or "retardation factor" in turbulent water flow	n	......	$L^{1/6}$
7	Depths in irrigation and drainage:			
	a. Root-zone soils	D_f	in. or ft	L
	b. Irrigation water applied	d	in. or ft	L
	c. Soil moistened	D	in. or ft	L
	d. Water flowing on a border strip	y	in.	L
	e. Water flowing in a canal	d	ft	L
8	Diameter of a pipe or drain tile or a capillary tube	d	in.	L
9	Full drain spacing distance	S	ft	L
10	Efficiencies of:			
	a. Water conveyance	E_c	percent	......
	b. Water application	E_a	percent	......
	c. Irrigation	E_i	percent	......
	d. Pumping plant	E_p	percent	......
11	Force on unit weight of water in a pipe due to gravity and pressure difference	F	lb/lb	......
12	Flow length of water in canal or soil. Also, length of border covered with water at any time	l	ft	L

* The quantities presented here for convenience of reference are defined where first used. Some quantities considered in this book are not listed here.

TABLE QR (*Continued*)

Item	Quantity	Symbols	American Engineering Units	Force-Length-Time Dimensions
13	Gravity:			
	a. Force per unit mass. Also acceleration of gravity	g	lb/slug	L/T^2
	b. Component parallel to water surface on each pound	F_g	lb/lb	......
14	Heads as used in hydraulics, irrigation, and drainage:			
	a. Hydraulic head	$(p/w)+z$	ft	L
	b. Velocity head	$v^2/2g$	ft	L
	c. Pressure head	p/w	ft	L
	d. Tension head	h_t	ft	L
	e. Elevation head	z	ft	L
	f. Friction head in flow in canal or in soil	h_f	ft	L
	g. Discharge head for			
	(1) Weirs	H	ft	L
	(2) Orifices	h	ft	L
15	Heights of water in irrigation and drainage			
	a. Lift by pumps	h	ft	L
	b. Column of water in a capillary tube or in an unsaturated soil column	h	in. or ft	L
	c. Water table above datum in saturated soils	H	ft	L
	d. Water surface in drain or at well above datum	h	ft	L
	e. Submerged orifice opening, height of	H	ft	L
16	Hydraulic radius: section area divided by wetted perimeter	r	sq ft/ft	L
17	Hydraulic slope or gradient: loss of head divided by flow length	$h_f/1$	ft/ft	......
18	Infiltration rate of water into soil	I	in./hr	L/T
19	Lengths of:			
	a. Weir crest, measured	L'	ft	L
	b. Weir crest, effective	L	ft	L
	c. Open or closed drain	L	ft	L
20	Mechanical energy of water at any point in a stream	E	ft-lb	LF
	a. Per unit weight	E_w	ft-lb/lb	L
	b. Per unit mass	E_m	ft-lb/slug	L^2/T^2
	c. Per unit volume	E_v	ft-lb/cu ft	F/L^2
21	Moisture percentages in soils:			
	a. Weight basis	P_w	percent	......
	(1) Field capacity	P_{fc}	percent	......
	(2) Wilting point	P_{wp}	percent	......
	(3) Available capacity	P_{ac}	percent	......
	(4) Moisture equivalent	P_{me}	percent	......
	b. Volume basis	P_v	percent	......

TABLE QR (*Concluded*)

Item	Quantity	Symbols	American Engineering Units	Force-Length-Time Dimensions
22	Percolation rates of water into soil (See also infiltration)	I	in./hr	L/T
23	Permeability of soils to water—velocity at unit hydraulic slope	k	ft/sec or in./hr or ft/yr	L/T
24	Pore space or porosity in soils	S	percent	......
25	Pressures per unit area:			
	a. Compression	p or p_c	psi	F/L^2
	b. Tension	t	psi	F/L^2
	c. Pressure differences $(p_2 - p_1)$	p'	psi	F/L^2
26	Quantity of flow of water	Q or q	cfs	L^3/T
27	Space between drains	S	ft	L
28	Specific *gravity* of water or soils:			
	a. Apparent (vol. wt.)	A_s	ratio	......
	b. Real	R_s	ratio	......
29	Specific *weight* of water or soil	w	lb/cu ft	F/L^3
30	Specific water conductivity of soils	k_c	sec or hr or yr	T
31	Surface tension	T	lb/in.	F/L
32	Temperature, mean monthly	t	degrees F	......
33	Time rate of water application	R	cfs/ac	L/T
34	Time water applied on a border strip	t	hr	T
35	Time water used for irrigation of an area	t	hr	T
36	Velocity of water flow, mean	v	ft/sec	L/T
37	Viscosity of water, dynamic	u	lb-sec/ft²	FT/L^2
38	Water and the farm:			
	a. Delivered to a farm or all farms	W_f	ft/yr	L/T
	b. Runoff from the farm	R_f	ft/yr	L/T
	c. Stored in the farm root-zone soil	W_s	ft/yr	L/T
	d. Consumed by each farm crop	W_c or U	in. or ft per mo. or yr	L/T
	e. Lost by deep percolation	D_f	ft/yr	L/T
	f. Diverted from river for farms	W_r	ft/yr	L/T

designated as $\frac{1}{50}$ of a cu ft per sec in southern California, Idaho, Kansas, New Mexico, North Dakota, South Dakota, Nebraska, and Utah. In Arizona, northern California, Montana, Nevada, and Oregon, 1 miner's inch is equal to $\frac{1}{40}$ of a cu ft per sec. In Colorado 38.4 miner's inches is considered equal to 1 cu ft per sec.

17. Velocity of Flow through an Orifice When the water-pressure intensity inside the pipes of a domestic water system is high the water flows out of an open tap at a high velocity, and when the pressure is

low it flows out slowly. If the water pressure within the pipe were exactly equal to the pressure of the air outside the pipe there would be no flow. Pressure intensity at any point within a body of water with a free surface is proportional to the depth of the point below the water surface. The velocity of water through an opening in a vessel (or in a wall built across a stream) which is far below the water surface is greater than the velocity through an opening near the water surface. In irrigation practice it is important to know just what the velocity will be through an orifice at any vertical distance below the water surface. The basic physical law which determines the velocity of water through an orifice is the same as the law which determines the velocity of a falling body at any vertical distance below the point from which it began to fall.

The velocity of a falling body, ignoring atmospheric friction, may be determined by knowing the vertical distance through which the body has fallen from rest. Likewise, the velocity of water escaping from an opening (orifice) in a vessel, ignoring friction, may be determined by knowing the height of the water in the vessel above the opening. Stated as an equation, this very important law of falling bodies, as applied to the flow of water, is

$$v = \sqrt{2gh} \tag{2}$$

where v = velocity in feet per second;

g = the acceleration due to gravity (or the force of gravity per unit mass of water), which is 32.2 ft per sec per sec;

h = the depth of water in feet, or pressure head, causing the discharge through the orifice.

If the vertical dimension of the orifice opening is very long, the velocity of flow through the orifice will be appreciably greater near the bottom of the orifice than near the top. For the purpose of this discussion it is assumed that the orifice height is so small as compared to the pressure head causing the discharge that the difference between velocity near the top and near the bottom of the orifice is negligible. To illustrate the use of equation 2 assume that h in Fig. 11 = 4 ft. Then

$$v = \sqrt{2 \times 32.2 \times 4} = 16.04 \text{ ft per sec}$$

i.e., theoretically, water should flow through an orifice which is 4 feet below the surface at a velocity of approximately 16 feet per second. Owing to frictional resistance, the actual velocity is somewhat less than the theoretical velocity.

The quantity of water that flows through an opening, or in a channel, is directly proportional to the cross-section area of the opening or channel and to the velocity of flow. The basic rational equation for quantity of flow is:

$$q = av \tag{3}$$

where q^* = quantity of flow, cubic feet per second;
a = cross-sectional area of water, the canal or orifice, in square feet;
v = the mean velocity, feet per second.

18. Discharge through an Orifice The *theoretical* discharge through an orifice may be determined by substituting the value of v from equation 2 in the *quantity* equation, i.e.,

$$q = a\sqrt{2gh} \tag{3a}$$

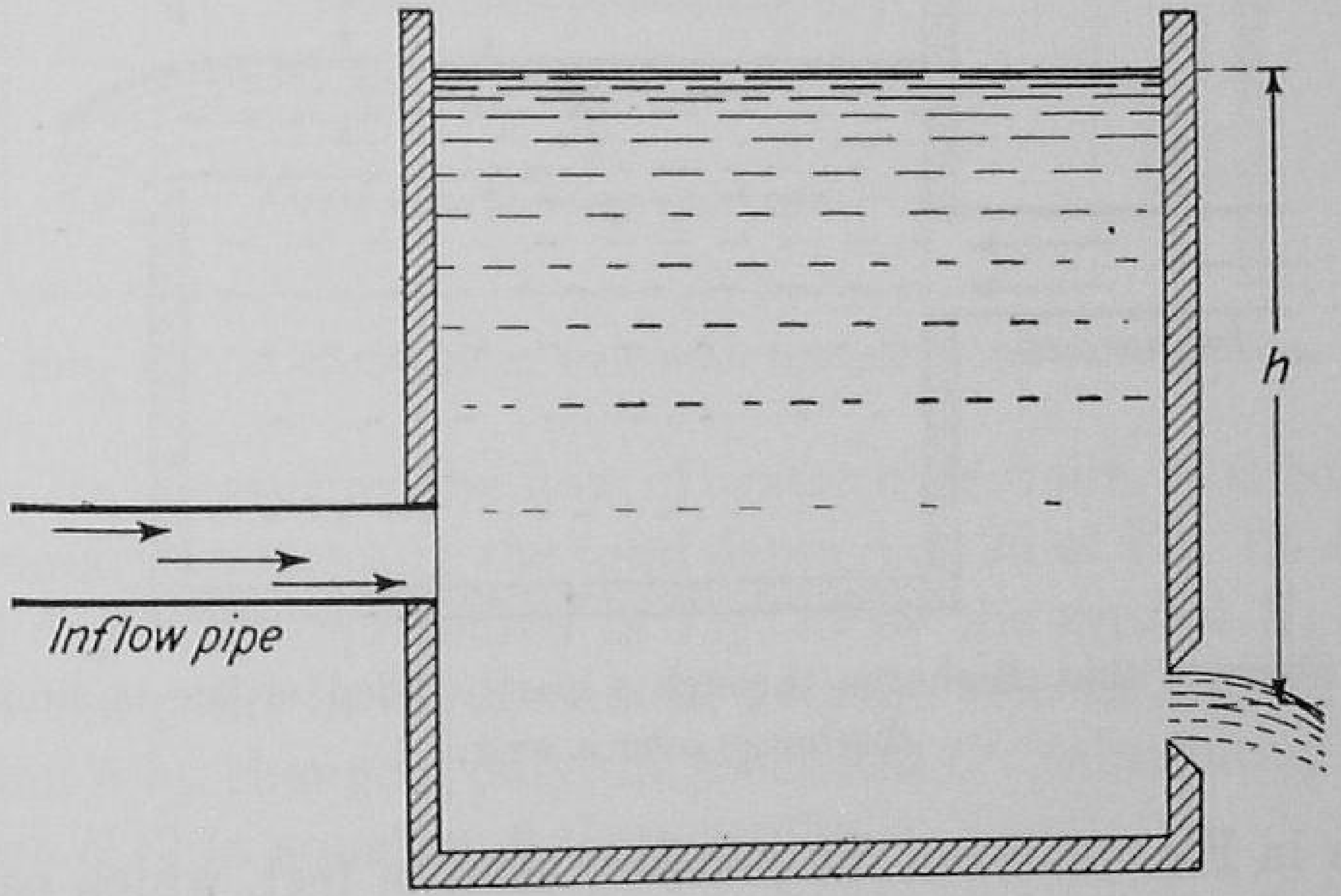

FIG. 11. Illustrating the discharge of water through an orifice under a head, h.

If the orifice opening in Fig. 11 were 4 in. high by 18 in. long (perpendicular to the plane of the paper), the area would be

$$a = \frac{4 \times 18}{144} = \frac{1}{2} \text{ sq ft}$$

Experiment has shown that the actual discharge for standard orifice is approximately six-tenths the theoretical discharge, so that the actual q would be computed thus:

$$q = \tfrac{6}{10} \times \tfrac{1}{2} \times \tfrac{16}{1} = 4.8 \text{ cfs}$$

* Table QR shows that the physical dimensions of q are L^3/T; also that $a = L^2$ and $v = L/T$. Therefore, the product $av = L^2 \times L/T = L^3/T$, which is q, volume per unit time.

Finally, the equation for actual discharge through an orifice is

$$q = Ca\sqrt{2gh} \tag{4}$$

in which C is a coefficient of discharge determined by experiment. The coefficient C ranges from 0.6 up to 0.8 or more, depending on the position of the orifice relative to the sides and bottom of the vessels or of the water channel, and also on the degree of roundness of the edges of the orifice.

Suppose that the height of the orifice is increased and that the water surface is lowered until it drops below the upper edge of the orifice,

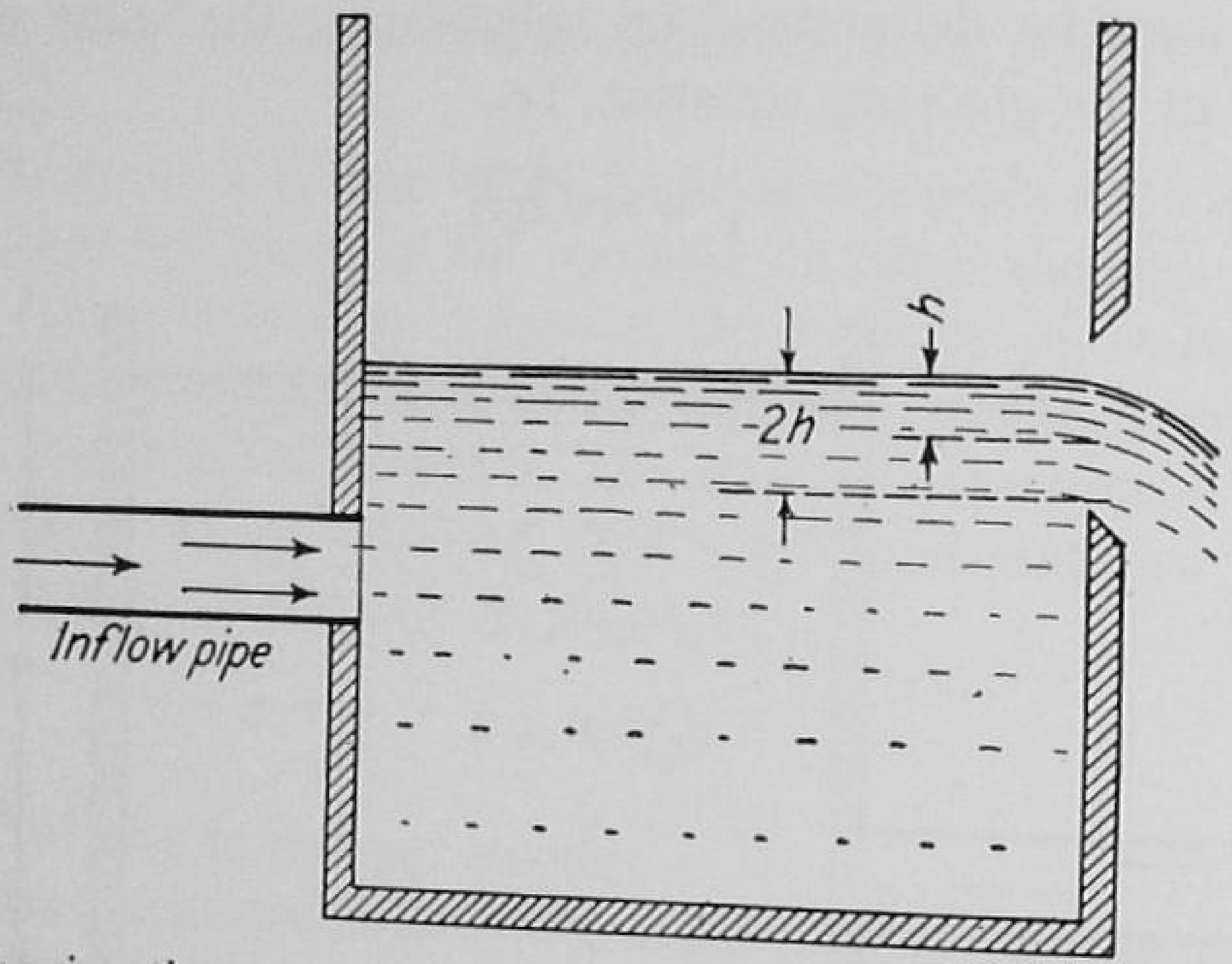

FIG. 12. Showing that discharge through a partly filled orifice is similar to the discharge over a weir.

as shown in Fig. 12. Then the pressure head in feet, which causes the average velocity, as represented by h of Fig. 12 is one-half of the total depth of water over the bottom edge of the orifice. The cross-section area of the stream at right angles to the direction of flow is actually less than the cross-section area of the orifice. The length of orifice being 18 in. or 1.5 ft, the cross-section area of the stream is

$$a = 2h \times 1.5 \text{ sq ft}$$

or, representing the length of orifice by the symbol L measured in feet,

$$a = 2hL \text{ sq ft}$$

Substituting this value of a in equation 4

$$q = 2CLh\sqrt{2gh} = 2CLh^{3/2}\sqrt{2g} \tag{5}$$

Since the acceleration due to gravity, g, is nearly constant, it is con-

AG32

venient to represent the product $2C\sqrt{2g}$ by a single symbol, say C', and then it follows that

$$q = C'Lh^{3/2} \tag{6}$$

Equation 6 gives the theoretical discharge of an orifice when the top edge of the orifice is above the water surface.

19. Discharge of Weirs The term weir as used in measurement of water is defined as a notch in a wall built across a stream. The notch may be *rectangular, trapezoidal,* or *triangular* in shape. The orifice in Fig. 12, when flowing partly full, is a weir according to the above

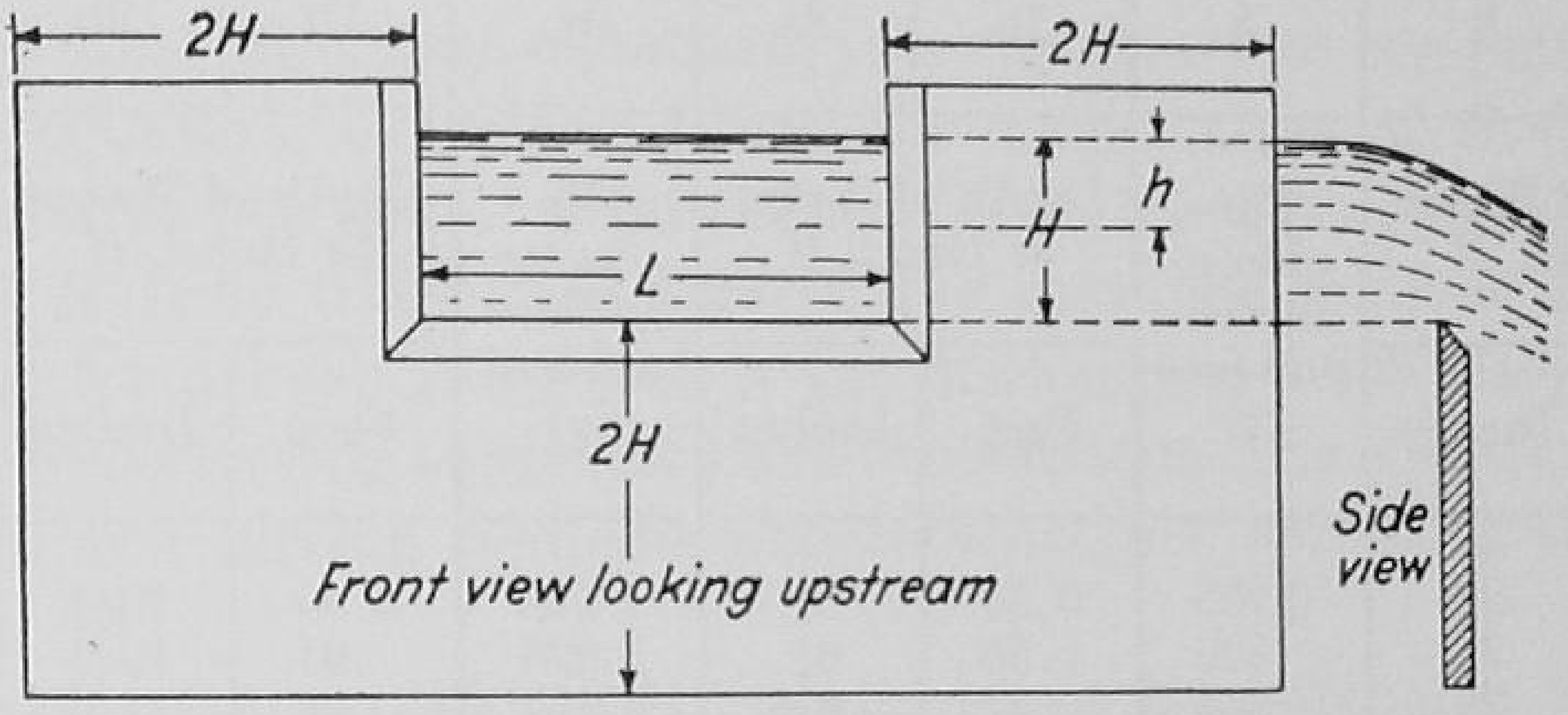

FIG. 13. A rectangular weir with complete end contractions.

definition. In measuring the flow of water over weirs, it is convenient and customary to measure the total depth, i.e., $2h$ of Fig. 12. Although the total depth, as represented in Fig. 13 by the symbol H, does not represent the point in the stream of average velocity, it can be used in equation 6 by changing only the coefficient C'. Substituting for h its equivalent $H/2$ in equation 6 there results

$$q = C'L\left(\frac{H}{2}\right)^{3/2} = \frac{C'}{2^{3/2}} LH^{3/2}$$

or

$$q = C'' LH^{3/2} \tag{7}$$

in which*

$$C'' = \frac{C'}{2^{3/2}}$$

Equation 7 is the general form for discharge of rectangular and trapezoidal weirs. Although, as shown above, it is based on the funda-

* Table QR shows that the length-time dimensions of C'' for equation 7 are $L^{1/2}T^{-1}$. By substitution, it follows that

$$\frac{L^3}{T} = \frac{L^{1/2}}{T} L^{2/2}L^{3/2} = \frac{L^3}{T}$$

and that equation 7 is homogeneous.

mental equation $q = av$, the student should note that in using equation 7 the only measurements essential are those of length of weir crest, L, and depth of water flowing over it, H. The velocity need not be measured directly. The coefficient C'', ordinarily represented by C, has been determined by experiment by many workers. For rectangular weirs it was early found by Francis to be 3.33, and hence

TABLE 1

Discharge in Cubic Feet per Second (Second-feet) per Foot of Length of Weir Crest by the Francis Formula: $q = 3.33\ H^{3/2}$

1	2	3	1a	2a	3a	1b	2b	3b
Depth of Water or Head, H		Discharge in Second-feet (q)	Depth of Water or Head, H		Discharge in Second-feet (q)	Depth of Water or Head, H		Discharge in Second-feet (q)
Feet	Inches		Feet	Inches		Feet	Inches	
0.20	$2\frac{3}{8}$	0.298	0.55	$6\frac{5}{8}$	1.358	0.90	$10\frac{13}{16}$	2.843
.21	$2\frac{1}{2}$	.320	.56	$6\frac{3}{4}$	1.395	.91	$10\frac{15}{16}$	2.890
.22	$2\frac{5}{8}$	.344	.57	$6\frac{13}{16}$	1.433	.92	$11\frac{1}{16}$	2.938
.23	$2\frac{3}{4}$	.367	.58	$6\frac{15}{16}$	1.470	.93	$11\frac{3}{16}$	2.986
.24	$2\frac{7}{8}$	.392	.59	$7\frac{1}{16}$	1.509	.94	$11\frac{1}{4}$	3.035
.25	3	.416	.60	$7\frac{3}{16}$	1.547	.95	$11\frac{3}{8}$	3.083
.26	$3\frac{1}{8}$	.442	.61	$7\frac{5}{16}$	1.586	.96	$11\frac{1}{2}$	3.132
.27	$3\frac{1}{4}$	.467	.62	$7\frac{7}{16}$	1.626	.97	$11\frac{5}{8}$	3.181
.28	$3\frac{3}{8}$	.493	.63	$7\frac{9}{16}$	1.665	.98	$11\frac{3}{4}$	3.230
.29	$3\frac{1}{2}$	.520	.64	$7\frac{11}{16}$	1.705	.99	$11\frac{7}{8}$	3.280
.30	$3\frac{5}{8}$	.547	.65	$7\frac{13}{16}$	1.745	1.00	12	3.300
.31	$3\frac{3}{4}$	.575	.66	$7\frac{15}{16}$	1.785	1.01	$12\frac{1}{8}$	3.380
.32	$3\frac{13}{16}$	.603	.67	$8\frac{1}{16}$	1.826	1.02	$12\frac{1}{4}$	3.430
.33	$3\frac{15}{16}$	.631	.68	$8\frac{3}{16}$	1.867	1.03	$12\frac{3}{8}$	3.481
.34	$4\frac{1}{16}$	.660	.69	$8\frac{1}{4}$	1.908	1.04	$12\frac{1}{2}$	3.532
.35	$4\frac{3}{16}$	.689	.70	$8\frac{3}{8}$	1.950	1.05	$12\frac{5}{8}$	3.583
.36	$4\frac{5}{16}$	.719	.71	$8\frac{1}{2}$	1.992	1.06	$12\frac{3}{4}$	3.634
.37	$4\frac{7}{16}$	.749	.72	$8\frac{5}{8}$	2.034	1.07	$12\frac{13}{16}$	3.686
.38	$4\frac{9}{16}$	.780	.73	$8\frac{3}{4}$	2.070	1.08	$12\frac{15}{16}$	3.737
.39	$4\frac{11}{16}$	.811	.74	$8\frac{7}{8}$	2.120	1.09	$13\frac{1}{16}$	3.789
.40	$4\frac{13}{16}$	.842	.75	9	2.163	1.10	$13\frac{3}{16}$	3.842
.41	$4\frac{15}{16}$	.874	.76	$9\frac{1}{8}$	2.206	1.11	$13\frac{5}{16}$	3.894
.42	$5\frac{1}{16}$	.906	.77	$9\frac{1}{4}$	2.250	1.12	$13\frac{7}{16}$	3.947
.43	$5\frac{3}{16}$	.939	.78	$9\frac{3}{8}$	2.294	1.13	$13\frac{9}{16}$	4.000
.44	$5\frac{1}{4}$	.972	.79	$9\frac{1}{2}$	2.340	1.14	$13\frac{11}{16}$	4.053
.45	$5\frac{3}{8}$	1.005	.80	$9\frac{5}{8}$	2.383	1.15	$13\frac{13}{16}$	4.107
.46	$5\frac{1}{2}$	1.039	.81	$9\frac{3}{4}$	2.428	1.16	$13\frac{15}{16}$	4.160
.47	$5\frac{5}{8}$	1.073	.82	$9\frac{13}{16}$	2.473	1.17	$14\frac{1}{16}$	4.214
.48	$5\frac{3}{4}$	1.107	.83	$9\frac{15}{16}$	2.520	1.18	$14\frac{3}{16}$	4.268
.49	$5\frac{7}{8}$	1.142	.84	$10\frac{1}{16}$	2.564	1.19	$14\frac{1}{4}$	4.323
.50	6	1.177	.85	$10\frac{3}{16}$	2.610	1.20	$14\frac{3}{8}$	4.377
.51	$6\frac{1}{8}$	1.213	.86	$10\frac{5}{16}$	2.660	1.21	$14\frac{1}{2}$	4.432
.52	$6\frac{1}{4}$	1.249	.87	$10\frac{7}{16}$	2.702	1.22	$14\frac{5}{8}$	4.487
.53	$6\frac{3}{8}$	1.285	.88	$10\frac{9}{16}$	2.749	1.23	$14\frac{3}{4}$	4.543
.54	$6\frac{1}{2}$	1.321	.89	$10\frac{11}{16}$	2.796	1.24	$14\frac{7}{8}$	4.598

the widely used sharp-crested weir discharge equation

$$q = 3.33LH^{3/2} \tag{8}$$

Equation 8 without modification applies accurately only to rectangular weirs in which the length of weir is the same as the width of the rectangular channel immediately above the weir, i.e., weirs having *suppressed* end contractions. For weirs having *complete* end contractions, such as represented in Fig. 13, the effective length of weir crest, L, is found from the relation

$$L = L' - 0.2H \tag{9}$$

in which L' = the measured length of weir crest. In actual use of equation 8 and other discharge equations, it is customary to compute tables from the equation, using $L = 1$, and for many values of H. Table 1 gives discharge per foot of length of weir crest based on equation 8 for values of H from 0.20 up to 1.24 ft. For example, columns 1 and 3 show that for a head H of 0.45 ft the discharge is 1.005 cfs per foot length of weirs having *suppressed* end contractions. The effective length for a 1-ft weir having *complete* end contractions, according to equation 9, is

$L = 1.00 - 0.2 \times 0.45 = 0.91$ ft, and hence the discharge per foot of measured length is $1.005 \times 0.91 = 0.9145$ cfs.*

An Italian engineer named Cipolletti long ago designed a trapezoidal weir with complete contractions in which the discharge is believed to

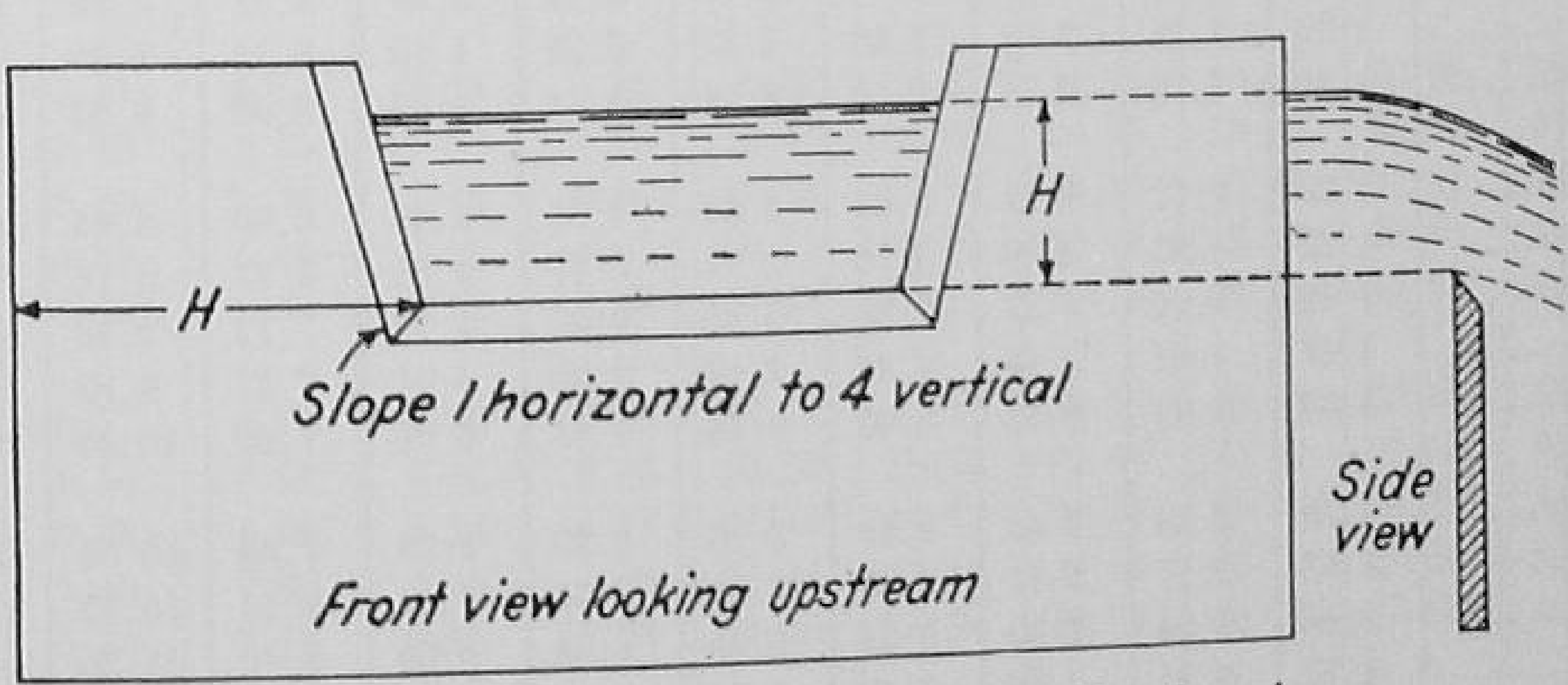

FIG. 14. A trapezoidal or Cipolletti weir.

be directly proportional to the length of weir crest. For irrigation purposes this weir has some advantages. It has been widely used. The equation giving the discharge is:

$$q = 3.367LH^{3/2} \tag{10}$$

In this weir the sides have a slope of 1 in. horizontal to 4 in. vertical, as shown in Fig. 14. Aside from the small correction necessary on

* To clarify understanding of equation 8, the student may compute discharges per foot of length for other values of H and check with Table 1.

TABLE 2

Discharge Over Cipolletti's Trapezoidal Weir. For Various Lengths and Heads. Formula: $q = 3.367LH^{3/2}$

Head H on Crest		Length of Weir Crest in Feet											
In Feet	In Inches	1	1½	2	2½	3	3½	4	5	7½	10	12½	15
		Discharge in Cubic Feet per Second											
0.21	2½	0.324	0.49	0.65	0.81	0.97	1.13	1.30	1.62	2.43	3.24	4.05	4.86
.22	⅝	.347	.52	.69	.87	1.04	1.22	1.39	1.74	2.61	3.47	4.34	5.21
.23	¾	.371	.56	.74	.93	1.11	1.30	1.49	1.86	2.79	3.71	4.64	5.57
.24	⅞	.396	.59	.79	.99	1.19	1.39	1.58	1.98	2.97	3.96	4.95	5.94
.25	3	.421	.63	.84	1.05	1.26	1.47	1.68	2.10	3.16	4.21	5.26	6.31
.26	3⅛	.446	.67	.89	1.12	1.34	1.56	1.79	2.23	3.35	4.46	5.58	6.70
.27	¼	.472	.71	.94	1.18	1.42	1.65	1.89	2.36	3.54	4.72	5.90	7.09
.28	⅜	.499	.75	1.00	1.25	1.50	1.75	2.00	2.49	3.74	4.99	6.24	7.48
.29	½	.526	.79	1.05	1.31	1.58	1.84	2.10	2.63	3.94	5.26	6.57	7.89
.30	⅝	.553	.83	1.11	1.38	1.66	1.94	2.21	2.77	4.15	5.53	6.92	8.30
.31	3¾	....	.87	1.16	1.45	1.74	2.03	2.32	2.91	4.36	5.81	7.26	8.72
.32	⅞	....	.91	1.22	1.52	1.83	2.13	2.44	3.05	4.57	6.09	7.62	9.14
.33	4	....	.96	1.28	1.60	1.91	2.23	2.55	3.19	4.79	6.38	7.98	9.57
.34	⅛	....	1.00	1.33	1.67	2.00	2.34	2.67	3.34	5.01	6.67	8.34	10.01
.35	¼	....	1.05	1.39	1.74	2.09	2.44	2.79	3.49	5.23	6.97	8.71	10.46
.36	4⅜	....	1.09	1.45	1.82	2.18	2.56	2.91	3.64	5.45	7.27	9.09	10.91
.37	½	....	1.14	1.52	1.89	2.27	2.65	3.03	3.79	5.68	7.58	9.47	11.37
.38	9/16	....	1.18	1.58	1.97	2.37	2.76	3.15	3.94	5.91	7.89	9.86	11.83
.39	⅝	....	1.23	1.64	2.05	2.46	2.87	3.28	4.10	6.15	8.20	10.25	12.30
.40	¾	....	1.28	1.70	2.13	2.56	2.98	3.41	4.26	6.39	8.52	10.65	12.78
.41	4⅞	....	1.33	1.77	2.21	2.65	3.09	3.54	4.42	6.63	8.84	11.05	13.26
.42	5	....	1.37	1.83	2.29	2.75	3.21	3.67	4.58	6.87	9.16	11.46	13.75
.43	⅛	....	1.42	1.90	2.37	2.85	3.32	3.80	4.75	7.12	9.49	11.87	14.24
.44	¼	....	1.47	1.97	2.46	2.95	3.44	3.93	4.91	7.37	9.83	12.28	14.74
.45	⅜	....	1.52	2.03	2.55	3.05	3.56	4.07	5.08	7.62	10.16	12.70	15.24
.46	5½	....	1.58	2.10	2.63	3.15	3.68	4.20	5.25	7.88	10.50	13.13	15.76
.47	⅝	....	1.63	2.17	2.71	3.25	3.80	4.34	5.42	8.14	10.85	13.56	16.27
.48	¾	....	1.68	2.24	2.80	3.36	3.92	4.48	5.60	8.40	11.20	14.00	16.79
.49	⅞	....	1.73	2.31	2.89	3.46	4.04	4.62	5.77	8.66	11.55	14.43	17.32
.50	6	....	1.79	2.38	2.98	3.57	4.17	4.76	5.95	8.93	11.90	14.88	17.85
.51	6⅛	....	1.84	2.45	3.07	3.68	4.29	4.90	6.13	9.20	12.26	15.33	18.39
.52	¼	....	1.89	2.52	3.16	3.79	4.42	5.05	6.31	9.47	12.62	15.78	18.94
.53	⅜	....	1.95	2.60	3.25	3.90	4.55	5.20	6.50	9.74	12.99	16.24	19.49
.54	½	....	2.00	2.67	3.34	4.01	4.68	5.34	6.68	10.02	13.36	16.70	20.04
.55	⅝	....	2.06	2.75	3.43	4.12	4.81	5.49	6.87	10.30	13.73	17.17	20.60
.56	6¾	....	2.12	2.82	3.53	4.23	4.94	5.64	7.05	10.58	14.11	17.64	21.16
.57	⅞	....	2.17	2.90	3.62	4.35	5.07	5.80	7.24	10.87	14.49	18.11	21.73
.58	7	....	2.23	2.97	3.72	4.46	5.20	5.95	7.44	11.15	14.87	18.59	22.31
.59	⅛	....	2.29	3.05	3.81	4.58	5.34	6.10	7.63	11.44	15.26	19.07	22.89
.60	¼	....	2.35	3.13	3.91	4.69	5.48	6.26	7.82	11.74	15.65	19.56	23.47

TABLE 2 (*Concluded*)

Head H on Crest: In Feet	Head H on Crest: In Inches	Length of Weir Crest in Feet: 2	2½	3	3½	4	5	7½	10	12½	15	18
		Discharge in Cubic Feet per Second										
0.61	7⅜	3.21	4.01	4.81	5.61	6.42	8.02	12.03	16.04	20.05	24.06	28.87
.62	½	3.29	4.11	4.93	5.75	6.57	8.22	12.33	16.44	20.54	24.65	29.58
.63	9/16	3.37	4.21	5.05	5.89	6.73	8.42	12.63	16.83	21.04	25.25	30.30
.64	⅝	3.45	4.31	5.17	6.03	6.89	8.62	12.93	17.24	21.55	25.86	31.03
.65	¾	3.53	4.41	5.29	6.18	7.06	8.82	13.23	17.64	22.05	26.46	31.76
.66	7⅞	3.61	4.51	5.42	6.32	7.22	9.03	13.54	18.05	22.56	27.08	32.49
.67	8	3.69	4.62	5.54	6.46	7.39	9.23	13.85	18.46	23.08	27.70	33.23
.68	⅛	3.78	4.72	5.66	6.61	7.55	9.44	14.16	18.88	23.60	28.32	33.98
.69	¼	3.86	4.82	5.79	6.75	7.72	9.65	14.47	19.30	24.12	28.94	34.73
.70	⅜	3.94	4.93	5.92	6.90	7.89	9.86	14.79	19.72	24.65	29.58	35.49
.71	8½	4.03	5.04	6.04	7.05	8.06	10.07	15.11	20.14	25.18	30.21	36.25
.72	⅝	4.11	5.14	6.17	7.20	8.23	10.28	15.43	20.57	25.71	30.85	37.03
.73	¾	4.20	5.25	6.30	7.35	8.40	10.50	15.75	21.00	26.25	31.50	37.80
.74	⅞	4.29	5.36	6.43	7.50	8.57	10.72	16.07	21.43	26.79	32.15	38.58
.75	9	4.37	5.47	6.56	7.65	8.75	10.93	16.40	21.87	27.33	32.80	39.36
.76	9⅛	4.46	5.58	6.69	7.81	8.92	11.15	16.73	22.31	27.88	33.46	40.15
.77	¼	4.55	5.69	6.82	7.96	9.10	11.37	17.06	22.75	28.43	34.12	40.95
.78	⅜	4.64	5.80	6.96	8.12	9.28	11.60	17.39	23.19	28.99	34.79	41.75
.79	½	4.73	5.91	7.09	8.27	9.46	11.82	17.73	23.64	29.55	35.46	42.55
.80	⅝	4.82	6.02	7.23	8.43	9.64	12.05	18.07	24.09	30.11	36.13	43.36
.81	9¾	4.91	6.14	7.36	8.59	9.82	12.27	18.41	24.54	30.68	36.81	44.18
.82	⅞	5.00	6.25	7.50	8.75	10.00	12.50	18.75	25.00	31.25	37.50	45.00
.83	10	5.09	6.36	7.64	8.91	10.18	12.73	19.09	25.46	31.82	38.19	45.82
.84	⅛	5.18	6.48	7.78	9.07	10.37	12.96	19.44	25.92	32.40	38.88	46.65
.85	¼	5.28	6.60	7.92	9.23	10.55	13.19	19.79	26.38	32.98	39.57	47.49
.86	10⅜	5.37	6.71	8.06	9.40	10.74	13.43	20.14	26.85	33.56	40.28	48.33
.87	½	5.46	6.83	8.20	9.56	10.93	13.66	20.49	27.32	34.15	40.97	49.18
.88	9/16	5.56	6.95	8.34	9.73	11.12	13.90	20.84	27.79	34.74	41.69	50.03
.89	⅝	5.65	7.07	8.48	9.89	11.31	14.13	21.20	28.27	35.33	42.40	50.88
.90	¾	5.75	7.19	8.62	10.06	11.50	14.37	21.56	28.75	35.93	43.12	51.74
.91	10⅞	....	7.31	8.77	10.23	11.69	14.61	21.92	29.23	36.53	43.84	52.61
.92	11	....	7.43	8.91	10.40	11.88	14.85	22.28	29.71	37.14	44.56	53.48
.93	⅛	....	7.55	9.06	10.57	12.08	15.10	22.65	30.19	37.74	45.29	54.35
.94	¼	....	7.67	9.20	10.74	12.27	15.34	23.01	30.68	38.35	46.02	55.23
.95	⅜	....	7.79	9.35	10.91	12.47	15.59	23.38	31.17	38.97	46.76	56.11
.96	11½	....	7.92	9.50	11.08	12.67	15.83	23.75	31.67	39.58	47.50	57.00
.97	⅝	....	8.04	9.65	11.26	12.87	16.08	24.12	32.16	40.20	48.24	57.89
.98	¾	....	8.17	9.80	11.43	13.06	16.33	24.49	32.66	40.83	48.99	58.79
.99	⅞	....	8.29	9.95	11.61	13.27	16.58	24.87	33.16	41.45	49.74	59.69
1.00	12	....	8.42	10.10	11.78	13.47	16.83	25.25	33.67	42.08	50.50	60.60

account of the fact that the sides of the weir slope outward, equation 10 may be arrived at in the same way as equation 8. Table 2 gives discharges for the trapezoidal weir as computed from equation 10 for length of crest from 1 to 18 ft.

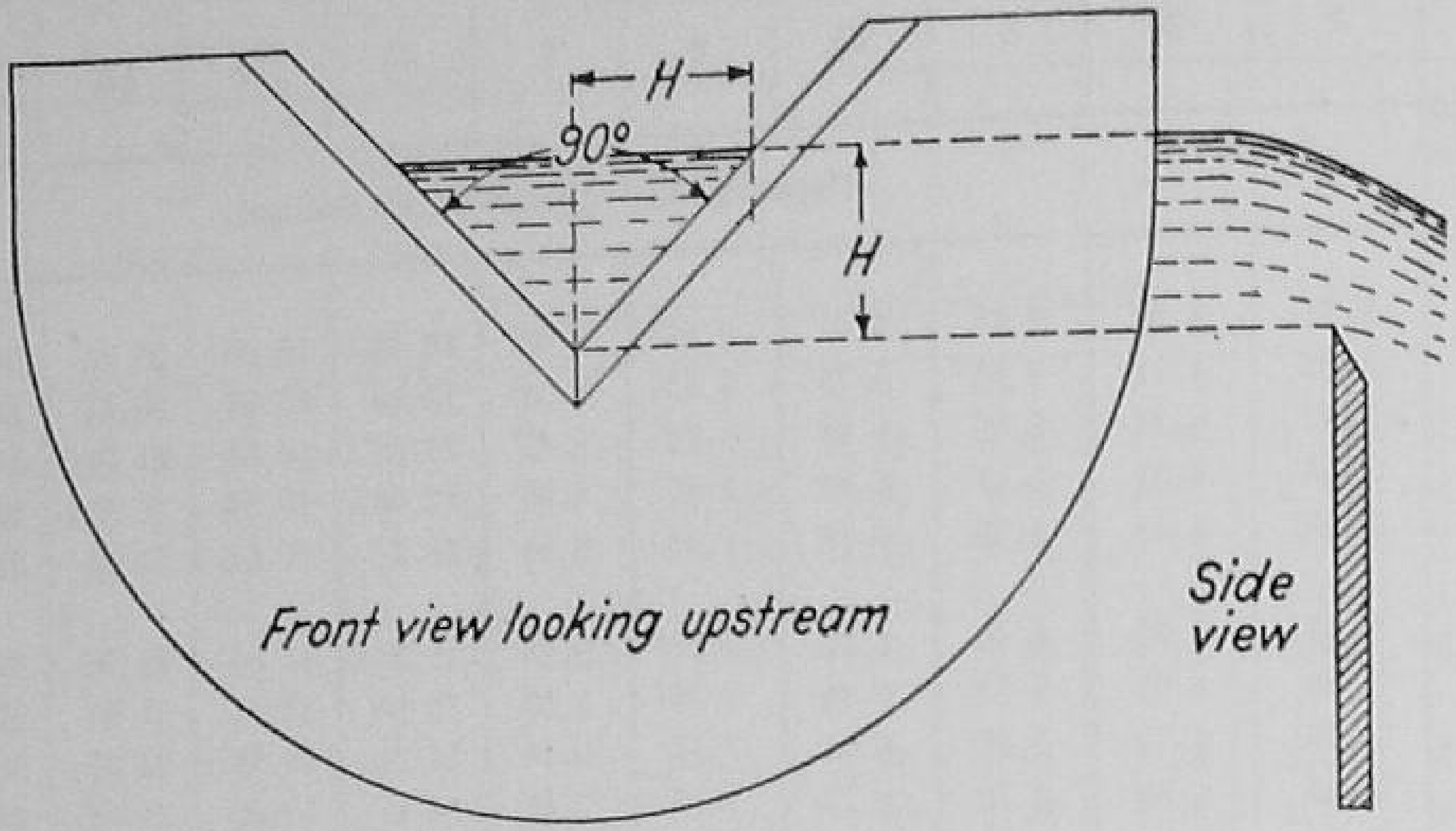

FIG. 15. A 90° triangular notch weir.

For the 90° triangular weir shown in Fig. 15, the water cross-section area is $H \times H$, or H^2, and therefore, from equation 4,

$$q = CH^2\sqrt{2gh} = C'H^{5/2}$$

is the theoretical discharge. The actual discharge has been found by experiment to be approximately

$$q = 2.49H^{5/2} \tag{11}$$

Table 3 gives discharges for the triangular weir.

20. Submerged Orifices The water cross-section area of a submerged orifice, Fig. 16, is the length of the opening times the height, or

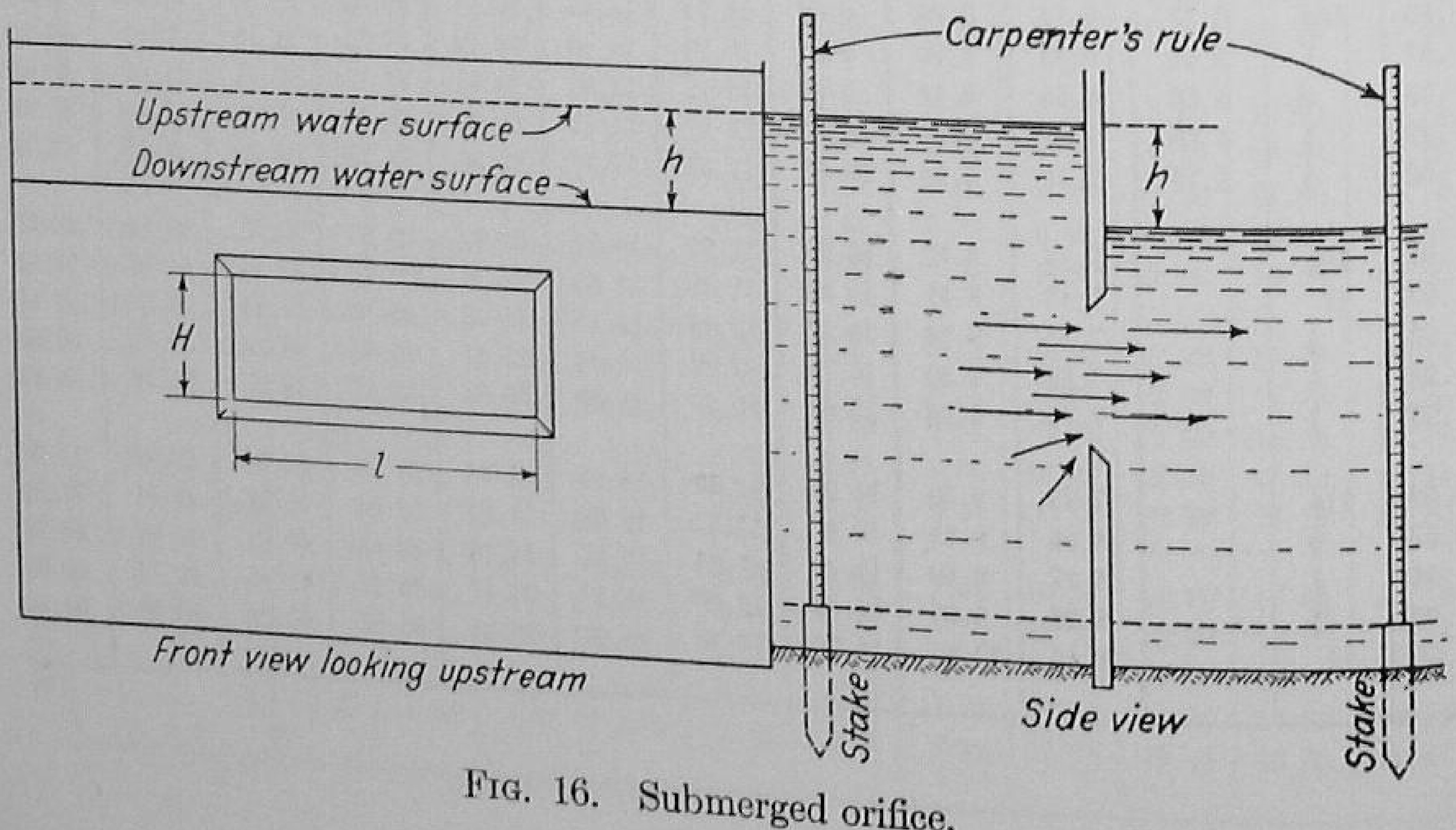

FIG. 16. Submerged orifice.

TABLE 3

Discharge Table for 90° Triangular Notch Weir*

Head in Feet	Head in Inches	Discharge in Second-feet (q)	Head in Feet	Head in Inches	Discharge in Second-feet (q)	Head in Feet	Head in Inches	Discharge in Second-feet (q)
0.20	$2\frac{3}{8}$	0.046	0.55	$6\frac{5}{8}$	0.564	0.90	$10\frac{13}{16}$	1.92
.21	$2\frac{1}{2}$	.052	.56	$6\frac{3}{4}$	.590	.91	$10\frac{15}{16}$	1.97
.22	$2\frac{5}{8}$	.058	.57	$6\frac{13}{16}$	.617	.92	$11\frac{1}{16}$	2.02
.23	$2\frac{3}{4}$	.065	.58	$6\frac{15}{16}$	.644	.93	$11\frac{3}{16}$	2.08
.24	$2\frac{7}{8}$	.072	.59	$7\frac{1}{16}$	.672	.94	$11\frac{1}{4}$	2.13
.25	3	.080	.60	$7\frac{3}{16}$	.700	.95	$11\frac{3}{8}$	2.19
.26	$3\frac{1}{8}$	.088	.61	$7\frac{5}{16}$	.730	.96	$11\frac{1}{2}$	2.25
.27	$3\frac{1}{4}$	.096	.62	$7\frac{7}{16}$	.760	.97	$11\frac{5}{8}$	2.31
.28	$3\frac{3}{8}$	.106	.63	$7\frac{9}{16}$	.790	.98	$11\frac{3}{4}$	2.37
.29	$3\frac{1}{2}$	.115	.64	$7\frac{11}{16}$	.822	.99	$11\frac{7}{8}$	2.43
.30	$3\frac{5}{8}$	.125	.65	$7\frac{13}{16}$	.854	1.00	12	2.49
.31	$3\frac{3}{4}$	.136	.66	$7\frac{15}{16}$	.887	1.01	$12\frac{1}{8}$	2.55
.32	$3\frac{13}{16}$	.147	.67	$8\frac{1}{16}$	.921	1.02	$12\frac{1}{4}$	2.61
.33	$3\frac{15}{16}$	.159	.68	$8\frac{3}{16}$	.955	1.03	$12\frac{3}{8}$	2.68
.34	$4\frac{1}{16}$	.171	.69	$8\frac{1}{4}$	.991	1.04	$12\frac{1}{2}$	2.74
.35	$4\frac{3}{16}$	.184	.70	$8\frac{3}{8}$	1.03	1.05	$12\frac{5}{8}$	2.81
.36	$4\frac{5}{16}$	.197	.71	$8\frac{1}{2}$	1.06	1.06	$12\frac{3}{4}$	2.87
.37	$4\frac{7}{16}$	.211	.72	$8\frac{5}{8}$	1.10	1.07	$12\frac{13}{16}$	2.94
.38	$4\frac{9}{16}$	.226	.73	$8\frac{3}{4}$	1.14	1.08	$12\frac{15}{16}$	3.01
.39	$4\frac{11}{16}$	.240	.74	$8\frac{7}{8}$	1.18	1.09	$13\frac{1}{16}$	3.08
.40	$4\frac{13}{16}$	.256	.75	9	1.22	1.10	$13\frac{3}{16}$	3.15
.41	$4\frac{15}{16}$	.272	.76	$9\frac{1}{8}$	1.26	1.11	$13\frac{5}{16}$	3.22
.42	$5\frac{1}{16}$	.289	.77	$9\frac{1}{4}$	1.30	1.12	$13\frac{7}{16}$	3.30
.43	$5\frac{3}{16}$	.306	.78	$9\frac{3}{8}$	1.34	1.13	$13\frac{9}{16}$	3.37
.44	$5\frac{1}{4}$	.324	.79	$9\frac{1}{2}$	1.39	1.14	$13\frac{11}{16}$	3.44
.45	$5\frac{3}{8}$	.343	.80	$9\frac{5}{8}$	1.43	1.15	$13\frac{13}{16}$	3.52
.46	$5\frac{1}{2}$	.362	.81	$9\frac{3}{4}$	1.48	1.16	$13\frac{15}{16}$	3.59
.47	$5\frac{5}{8}$	.382	.82	$9\frac{13}{16}$	1.52	1.17	$14\frac{1}{16}$	3.67
.48	$5\frac{3}{4}$	.403	.83	$9\frac{15}{16}$	1.57	1.18	$14\frac{3}{16}$	3.75
.49	$5\frac{7}{8}$	.424	.84	$10\frac{1}{16}$	1.61	1.19	$14\frac{1}{4}$	3.83
.50	6	.445	.85	$10\frac{3}{16}$	1.66	1.20	$14\frac{3}{8}$	3.91
.51	$6\frac{1}{8}$	.468	.86	$10\frac{5}{16}$	1.71	1.21	$14\frac{1}{2}$	3.99
.52	$6\frac{1}{4}$	.491	.87	$10\frac{7}{16}$	1.76	1.22	$14\frac{5}{8}$	4.07
.53	$6\frac{3}{8}$	.515	.88	$10\frac{9}{16}$	1.81	1.23	$14\frac{3}{4}$	4.16
.54	$6\frac{1}{2}$	.539	.89	$10\frac{11}{16}$	1.86	1.24	$14\frac{7}{8}$	4.24
						1.25	15	4.33

* Computed from the formula: $q = 2.49H^{2.48}$.

$A = l \times H$. The loss of head as water flows through a submerged orifice is the difference in elevation of the water surface upstream and downstream, as shown by h in Fig. 16. Hence from equation 4 and from experiments, the discharge for the standard submerged orifice is found to be

$$q = \tfrac{61}{100} lH\sqrt{2gh} \qquad (12)$$

The submerged orifice is used both in its standard form and as a

combination head-gate-measuring device. Table 4 gives discharges for submerged orifices as computed from equation 12. It shows, for example, that on a submerged orifice having an opening 6 in. high by 12 in. long (area 0.5 sq ft), if the upstream water surface is 3 in. or 0.25 ft higher than the downstream surface, the discharge will be 1.22 cfs.

21. Types of Orifices Used Types of orifices used to measure irrigation water are: (1) submerged orifices with fixed dimensions, (2) adjustable submerged orifices, (3) miner's-inch boxes, and (4) calibrated gates.

Submerged orifices with fixed dimensions are used where the available head is insufficient for weirs. For best results they are usually rectangular with the horizontal dimension from two to six times the height. They are generally installed in sufficiently large channels so that the contractions are complete or very nearly so. The coefficient will then be approximately 0.61. There is a lack of information regarding the coefficient for incomplete contractions. Submerged orifices should have a smooth vertical face of sufficient size, smooth sharp edges, accurate dimensions, and a provision for accurate head measurements.

There are several kinds of adjustable submerged orifices. Some resemble submerged orifices with fixed dimensions except that their height is adjustable to accommodate a wide range of flow without excessive loss of head. Table 4 may be used to determine the flow through orifices in which the channel is sufficiently large to insure complete end contractions. The more usual type of adjustable submerged orifice is a combination head gate, or turnout and measuring device. Such structures are usually made of wood and generally have one or two slide gates that may be held open in any desired position. Submerged orifice head gates are not accurate measuring devices and are gradually being replaced by better types of structures.

A development of recent years has been the calibrated commercial gates (Calco Meter Gates) for water measurement. Tests have been conducted on gates of various size and curves and tables prepared giving the flow in cubic feet per second for different gate openings measured on the rising stem. The head as determined is the difference in elevation of the water surface in the supply canal and the outlet ditch. Each Calco Meter Gate is calibrated individually, and a discharge chart and table are furnished with the gate at the time of purchase.

Many ingenious miner's-inch boxes have been devised; most of

TABLE 4

DISCHARGE TABLE FOR SUBMERGED RECTANGULAR ORIFICES*

Head H		Cross-sectional Area A of Orifice, square feet							
Feet	Inches	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00
0.09	$1\frac{1}{16}$	0.37	0.73	1.10	1.47	1.84	2.20	2.64	2.94
.10	$1\frac{3}{16}$	.39	.77	1.16	1.56	1.93	2.32	2.71	3.09
.11	$1\frac{5}{16}$	.41	.81	1.22	1.62	2.03	2.43	2.84	3.24
.12	$1\frac{7}{16}$	.42	.85	1.27	1.69	2.12	2.54	2.97	3.39
.13	$1\frac{9}{16}$	.44	.88	1.32	1.76	2.21	2.65	3.09	3.53
.14	$1\frac{11}{16}$	.46	.92	1.37	1.83	2.29	2.75	3.20	3.66
.15	$1\frac{13}{16}$	.47	.95	1.42	1.90	2.37	2.84	3.32	3.79
.16	$1\frac{15}{16}$	.49	.98	1.47	1.96	2.45	2.93	3.42	3.91
.17	$2\frac{1}{16}$	.50	1.01	1.51	2.02	2.52	3.02	3.53	4.03
.18	$2\frac{3}{16}$	.52	1.04	1.56	2.08	2.59	3.11	3.63	4.15
.19	$2\frac{1}{4}$	.53	1.07	1.60	2.13	2.67	3.20	3.73	4.26
.20	$2\frac{3}{8}$	.55	1.09	1.64	2.19	2.74	3.28	3.83	4.36
.21	$2\frac{1}{2}$	.56	1.12	1.68	2.24	2.80	3.36	3.92	4.48
.22	$2\frac{5}{8}$	.57	1.15	1.72	2.30	2.87	3.46	4.02	4.59
.23	$2\frac{3}{4}$	.59	1.17	1.76	2.35	2.93	3.52	4.10	4.69
.24	$2\frac{7}{8}$	.60	1.20	1.80	2.40	3.00	3.60	4.19	4.79
.25	3	.61	1.22	1.83	2.45	3.06	3.67	4.28	4.89
.26	$3\frac{1}{8}$	.62	1.25	1.87	2.49	3.12	3.74	4.37	4.99
.27	$3\frac{1}{4}$	.64	1.27	1.91	2.54	3.18	3.81	4.45	5.08
.28	$3\frac{3}{8}$	.65	1.29	1.94	2.59	3.24	3.88	4.53	5.18
.29	$3\frac{1}{2}$	.66	1.32	1.98	2.64	3.30	3.96	4.62	5.28
.30	$3\frac{5}{8}$	.67	1.34	2.01	2.68	3.35	4.02	4.69	5.36
.31	$3\frac{11}{16}$	.68	1.36	2.05	2.73	3.41	4.09	4.77	5.45
.32	$3\frac{13}{16}$	.69	1.38	2.07	2.76	3.46	4.15	4.84	5.53
.33	$3\frac{15}{16}$	.70	1.41	2.11	2.81	3.51	4.22	4.92	5.62
.34	$4\frac{1}{16}$	.71	1.43	2.14	2.85	3.57	4.28	4.99	5.70
.35	$4\frac{3}{16}$	.72	1.45	2.17	2.89	3.62	4.34	5.06	5.78
.36	$4\frac{5}{16}$	.73	1.47	2.20	2.93	3.67	4.40	5.14	5.87
.37	$4\frac{7}{16}$	.75	1.49	2.23	2.98	3.72	4.46	5.21	5.95
.38	$4\frac{9}{16}$	.75	1.51	2.26	3.02	3.77	4.52	5.28	6.03
.39	$4\frac{11}{16}$	.76	1.53	2.29	3.05	3.82	4.58	5.35	6.11
.40	$4\frac{13}{16}$	.77	1.55	2.32	3.09	3.87	4.64	5.42	6.19
.41	$4\frac{15}{16}$	.78	1.57	2.35	3.12	3.92	4.70	5.48	6.27
.42	$5\frac{1}{16}$	.79	1.59	2.38	3.17	3.96	4.75	5.55	6.34
.43	$5\frac{1}{8}$	.80	1.60	2.41	3.21	4.01	4.81	5.61	6.42
.44	$5\frac{1}{4}$	.81	1.62	2.43	3.24	4.06	4.87	5.68	6.49
.45	$5\frac{3}{8}$	.82	1.64	2.46	3.28	4.10	4.92	5.74	6.56
.46	$5\frac{1}{2}$	.83	1.66	2.49	3.32	4.15	4.98	5.81	6.64
.47	$5\frac{5}{8}$	.84	1.68	2.52	3.36	4.20	5.04	5.87	6.71
.48	$5\frac{3}{4}$	.85	1.70	2.54	3.39	4.24	5.08	5.93	6.78
.49	$5\frac{7}{8}$	.86	1.71	2.57	3.42	4.28	5.14	5.99	6.85
.50	6	.87	1.73	2.59	3.46	4.32	5.19	6.05	6.92
.51	$6\frac{1}{8}$	.87	1.75	2.62	3.49	4.37	5.24	6.11	6.99
.52	$6\frac{1}{4}$	.88	1.76	2.65	3.53	4.41	5.29	6.17	7.05
.53	$6\frac{3}{8}$	.89	1.78	2.67	3.56	4.45	5.34	6.23	7.12
.54	$6\frac{1}{2}$	.90	1.80	2.70	3.59	4.49	5.39	6.29	7.19
.55	$6\frac{9}{16}$	.91	1.81	2.72	3.63	4.53	5.44	6.35	7.25
.56	$6\frac{11}{16}$	.92	1.83	2.75	3.66	4.58	5.49	6.41	7.32
.57	$6\frac{13}{16}$	.92	1.85	2.77	3.69	4.62	5.54	6.46	7.38
.58	$6\frac{15}{16}$	.93	1.86	2.79	3.73	4.66	5.59	6.52	7.45
.59	$7\frac{1}{16}$	.94	1.88	2.82	3.76	4.70	5.64	6.58	7.51

* Computed from the formula: $q = 0.61\,A\,\sqrt{2g}\,\sqrt{H}$.

them contain an orifice plate with adjustable opening and some auxiliary means of regulating the required pressure head. The accuracy of measurement through any of these structures depends primarily upon (1) the ratio of head to height of orifice, (2) the accuracy with which the pressure head can be regulated or maintained, (3) the velocity of approach, (4) the accuracy with which the area of the orifice can be determined, (5) the conditions affecting the contraction of the jet, and (6) freedom from submergence.

For accurate measurements with free-flowing orifices, the height of the orifice should not be greater than the head used. The pressure head is the most difficult to regulate. The means generally employed is either an adjustable regulating gate or a spill crest at the desired level allowing excess water to overflow. Some of the miner's-inch boxes employ both principles to insure accurate measurement. With the complete contraction, velocity of approach is usually negligible.

22. Properties of Weirs and Orifices It is important to note the influence that change of depth of water, *H*, has on the discharge, *Q*, for the various weirs and orifices. For example, when the stream over a rectangular weir increases till the depth *H* is doubled, the cross-section area, *A*, is doubled, and the discharge increased by 2.8 times; whereas doubling *H* over a trapezoidal weir slightly more than doubles the area and increases the discharge proportionally. When the *H* on a triangular weir is doubled, the *A* (area) is increased 4 times and the discharge is increased nearly 5.66 times. When the depth of water, *H*, causing the discharge through a submerged orifice, is doubled, the area remains unchanged and the discharge, *Q*, is made only 1.4 times the original discharge. Comparisons similar to the above may readily be made for any change in depth by remembering that the discharge, *Q*, varies with the three-halves power of the depth, *H*, for the rectangular and trapezoidal weirs, with the five-halves power approximately for the triangular weir, and with the one-half power of the head, *h*, for the submerged orifice. The variations of discharge with depth of *H* have a very important bearing on irrigation practice and should be clearly understood by men in charge of water distribution.

In order to illustrate further the influence of change of depth on the discharge, the curves of Fig. 17 are presented. The above relations may be confirmed by examination of these curves and of Tables 1 to 4.

23. Advantages and Disadvantages of Weirs The advantages of weirs for water measurement are: (1) accuracy, (2) simplicity and ease of construction, (3) non-obstruction by moss or floating materials, and (4) durability.

The disadvantages of weirs are: (1) the requirement of considerable fall of the water surface, or loss in head, which makes their use in sections having level land impracticable, and (2) the collection of gravel, sand, and silt above the weir, which prevents accuracy of measurement.

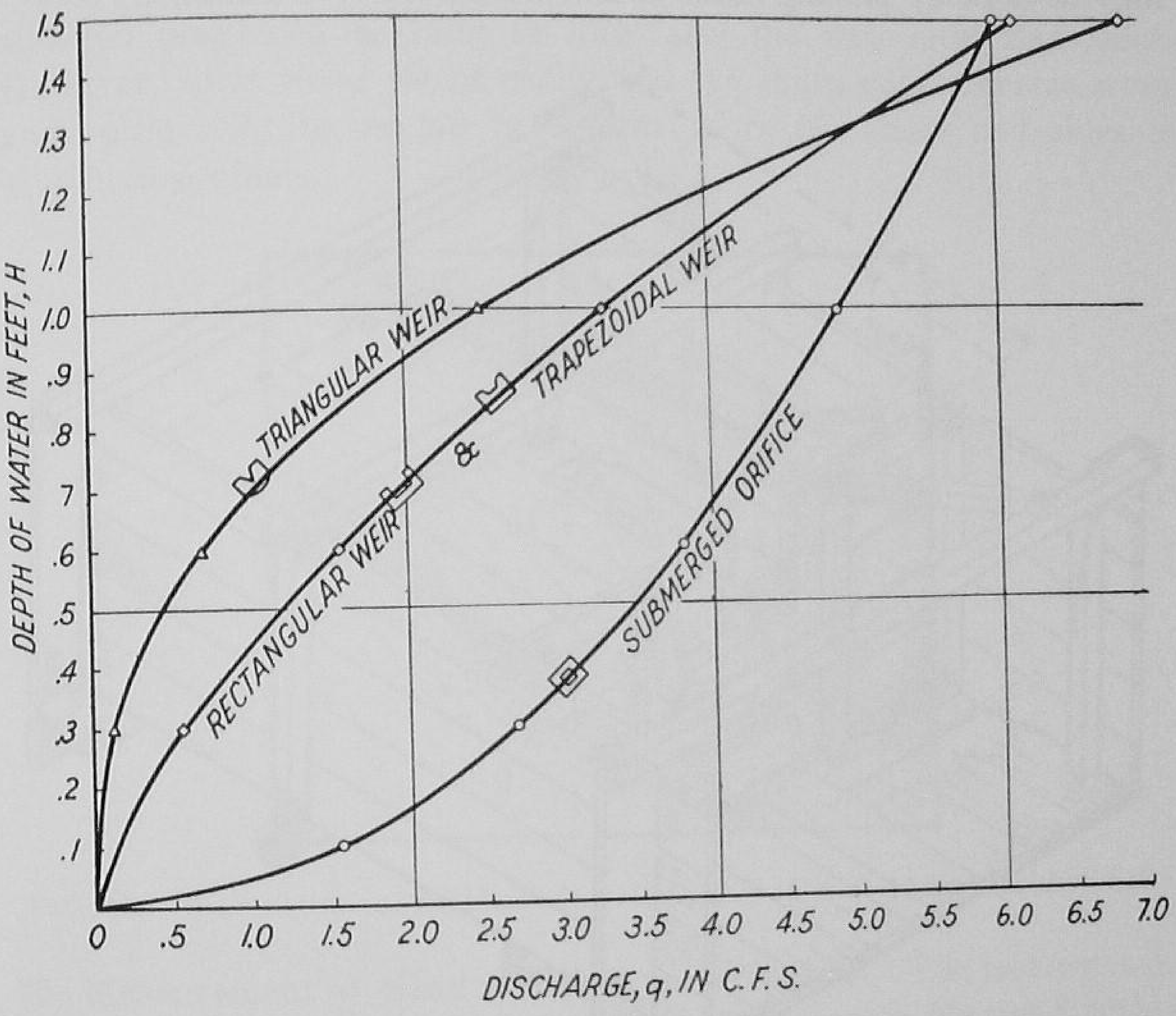

FIG. 17. Curves showing the relation between the discharge of water in cubic feet per second and the depth of water on the weir crest in feet for a 1-ft rectangular weir with suppressed end contractions, a 1-ft trapezoidal weir, a 90° triangular notch weir, and a submerged orifice of 1 sq ft cross-section area.

The principal advantage for the submerged orifice is the relatively small loss of head, making it suitable for use in canals and ditches having very small slopes where it is difficult to obtain fall enough to use weirs. Orifices have in addition most of the advantages enumerated for weirs.

The more serious disadvantages are: (1) collecting of floating debris, and (2) collecting of sand and silt above the orifice, thus preventing accurate measurement.

24. Weir Box and Pond In the use of either of the weirs above described, the ditch or canal must be made wider and deeper than the

the water surface will rise appreciably above the crest before flow over the crest begins. Small errors in reading H cause relatively large errors in the discharge determination. To show the error in measurement caused by an error in reading of only 0.01 ft, or less than ⅛ in., Table 6 is presented. The scale or gage may be marked to read cubic feet per second direct, and thus avoid the necessity of having to refer to a weir table to find the flow each time a reading is made.

TABLE 5

WEIR-BOX DIMENSIONS FOR RECTANGULAR, CIPOLLETTI, AND 90° TRIANGULAR NOTCH WEIRS

(All dimensions are in feet. The letters at the heads of the columns in this table refer to Fig. 18.)

Flow (Second-feet)	*H* Maximum Head	*L* Length of Weir Crest	*A* Length of Box Above Weir Notch	*K* Length of Box Below Weir Notch	*B* Total Width of Box	*E* Total Depth of Box	*C* End of Crest to Side	*D* Crest to Bottom	*F* Hook Gage Distance Upstream	*G* Hook Gage Distance Across Stream
Rectangular and Trapezoidal Weirs with End Contractions										
½ to 3	1.0	1	6	2	5½	3½	2¼	2	4	2
2 to 5	1.1	1½	7	3	7	4	2¾	2½	4½	2
4 to 8	1.2	2	8	4	8½	4½	3¼	2¾	5	2½
6 to 14	1.3	3	9	5	12	5	4½	3¼	5½	3
10 to 22	1.5	4	10	6	14	5½	5	3½	6	3
90° Triangular Notch Weir										
½ to 2½	1.00	..	6	2	5	3	2½	1½	4	2
2 to 4⅓	1.25	..	6½	8½	6½	3¼	3¼	1½	5	2½

Hook gages are widely used and considered the most accurate for determining water depths or stages. They consist of two essential parts: a movable scale on which is fastened a hook, and a fixed part containing an index mark and usually a vernier scale. The movable part is raised until the point produces a slight pimple on the water surface, and the gage height is read opposite the index. A blunt point is preferable to a sharp point.

Recording gages called water-level recorders are used to obtain a continuous graph of the gage height. The essential parts of a recording gage are: (1) a float or pressure-indicating device, (2) a recording

mechanism, and (3) a clock. Several different kinds of recording gages are available.

Stilling wells for measuring water elevation are essential if accuracy is desired. A box or piece of pipe set vertically at one side of the connected stream or channel is a stilling well. They are used to eliminate wave action and provide a still water surface. To function properly, the cross-sectional area of a stilling well should be about 100

TABLE 6

PERCENTAGE OF ERROR IN DISCHARGE OVER WEIRS CAUSED BY 0.01 FOOT ERROR IN READING THE HEAD

Head			Length of Weir Crest					90° Notch
Feet	Feet	Inches	Per cent 1 Foot	Per cent 1.5 Feet	Per cent 2 Feet	Per cent 3 Feet	Per cent 4 Feet	Per cent
0.20	0	2⅜	7.2	7.5	7.5	7.6	7.6	...
.30	0	3⅝	5.0	5.1	5.1	5.6	4.8	8.5
.50	0	6	3.5	3.2	3.0	2.9	2.9	5.0
.70	0	8⅜	2.1	1.9	2.1	2.2	2.2	3.9
.90	0	10 13/16	1.8	1.8	1.8	1.7	1.7	2.9
1.10	1	1 13/16	...	1.4	1.3	1.3	1.3	2.2
1.25	1	3	...	...	...	1.1	1.1	2.1
1.50	1	6	...	...	...	0.9	1.0	...

times the area of the inlet pipe or opening. Care should be taken to prevent the inlet pipe from clogging, and a convenient means of cleaning both the inlet pipe and the stilling well should be provided.

26. Portable Weirs It is sometimes desirable to measure small streams at points where the cost of the installation of permanent weirs would not be warranted. For example, the occasional measurement of surface runoff from various fields, though desirable, would hardly warrant the installation of a permanent weir. In situations like this, a small steel plate cut like a half circle and having a weir notch serves well. The notch may be cut as a rectangle, trapezoid, or triangle, depending on the type of weir desired.

Portable weirs are easily installed in ditches having sandy loam, loam, or clay loam bottoms and sides. Usually, in soils of these types, it is possible to drive the weir plate into the soil with a heavy hammer or an ax. In gravel soils a galvanized sheet metal Parshall flume is more easily installed than a weir plate. The flume is simply set in the ditch, and earth is filled in around the sides to force the water through the structure. Whether a weir or a flume is used, a carpenter's level is

necessary, to avoid getting one end of the weir crest higher than the other or to make sure that the upstream floor of the flume is exactly level. The depth of water flowing over the weir crest, or head, is measured by placing the end of a rule on a lug made for this purpose.

27. Weirs without End Contractions A standard rectangular weir without end contractions consists of a wall having a sharp crest built across a rectangular channel, high enough to cause a complete deflection of water filaments as the stream passes over the weir. The conditions for accuracy are the same as for the standard rectangular weir with contractions, except for those relating to side contractions. This type of weir can be used only in channels having a uniform rectangular cross section. Air holes must be made through the weir box just below the weir crest so as to fully admit air under the sheet of over-falling water.

The following rules for setting and operating weirs are helpful:

General Requirements for Proper Setting and Operating Weirs

1. The weir should be set at the lower end of a long pool sufficiently wide and deep to give an even, smooth current with a velocity of approach of not over 0.5 foot per second, which means practically still water.

2. The center line of the weir box should be parallel with the direction of the flow.

3. The face of the weir should be perpendicular, i.e., leaning neither upstream nor downstream.

4. The crest of the weir should be level, so the water passing over it will be of the same depth at all points along the crest, and sharp so that the over-falling water touches the crest at only one point.

5. The distance of the crest above the bottom of the pool should be about three times the depth of water flowing over the weir crest; the sides of the pool should be at a distance from the sides of the crest not less than twice the depth of the water passing over the crest.

6. The gage or weir scale may be placed on the upstream face of the weir structure and far enough to one side so that it will be in comparatively still water, as shown in Fig. 18, or it may be placed at any point in the weir pond or box, so long as it is a sufficient distance from the weir notch as to be beyond the downward curve of the water as it flows over the weir crest. The zero of the weir scale or gage should be placed level with the weir crest. This may be done with an ordinary carpenter's level or, where greater refinement is desired, with an engineer's level.

7. The crest should be placed high enough so the water will fall freely below the weir, leaving an air space under the over-falling sheet of water. If the water below the weir rises above the crest this free fall is not possible, and the weir is then said to be submerged. Unless complicated corrections are made, measurements on submerged weirs are unreliable.

8. For accurate measurements the depth over the crest should be no more than one-third the length of the crest.

9. The depth of water over the crest should be no less than 2 inches, as it is difficult with smaller depths to get sufficiently accurate gage readings to give close results.

10. To prevent washing by the falling water the ditch downstream from the weir should be protected by loose rock or by other material.

There are notable differences in opinion among irrigation authorities concerning the accuracy of the different weir formulas and the suitability of different water-measuring devices. The reader who desires further information concerning weirs, especially for precise measurements of water, should consult the references given at the end of the text.

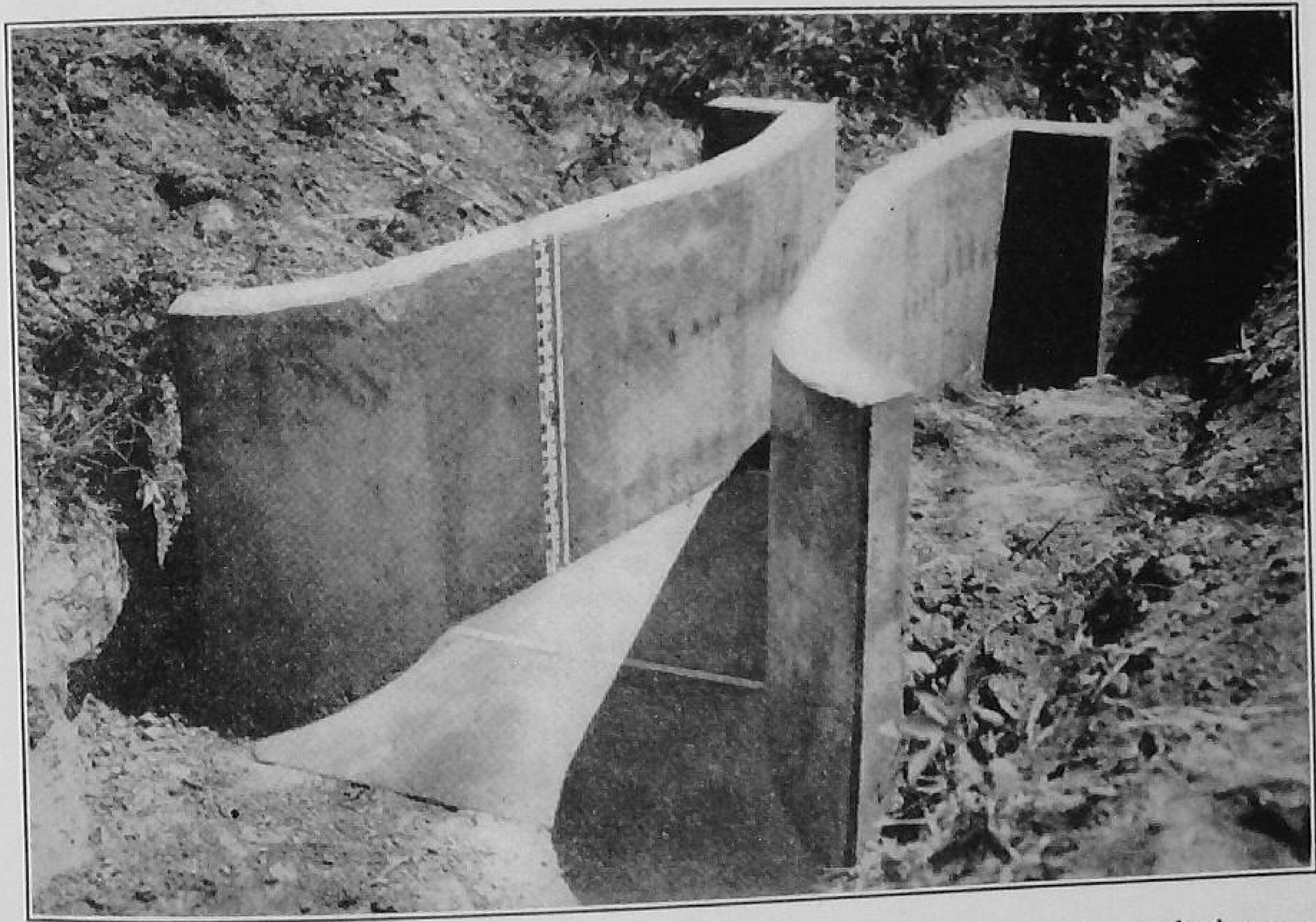

FIG. 20. Finished 9-in. Parshall flume with staff gage. One-inch angle irons at the upstream end, crest, and downstream end of the structure serve as guides for striking off the floors at exact elevations. (Courtesy Soil Conservation Service.)

28. Parshall Flumes Parshall has designed a measuring device with which the discharge is obtained by measuring the loss in head caused by forcing a stream of water through a throat or converged section of a flume with a depressed bottom. The disadvantages of weirs and submerged orifices are largely overcome by the Parshall flume. Since the head, H, on which the measurement is based is small, care must be exercised in determining the differences in water level to get accu-

rate measurements. The flume is illustrated in Figs. 20, 21, 22*A*, and 22*B*.

The Parshall measuring flume is a product of many years of painstaking research. It was first known as the Venturi flume, being similar to the Venturi tube or meter early designed to measure the flow of water in pipes. Some of the details concerning its design, construction, and use are presented here—others are available in the references for this chapter.

The accuracy of the Parshall measuring flume is within limits that are allowable in irrigation practice, ordinarily within 5 percent. Flumes

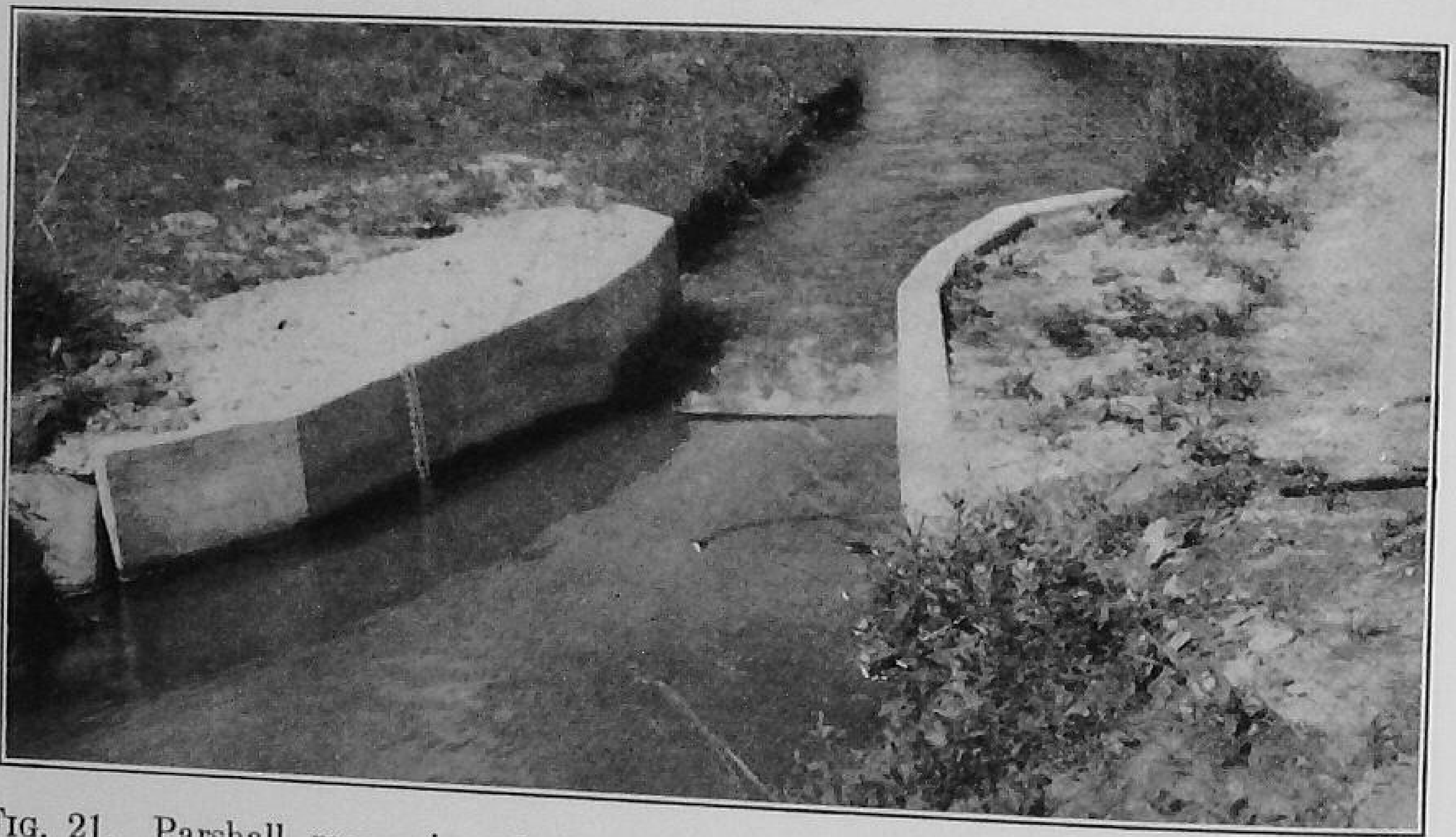

Fig. 21. Parshall measuring flume constructed with reinforced concrete, near Longmont, Colorado. (Courtesy Soil Conservation Service.)

ranging from 3 in. to 10 ft in throat width are used to measure flows from $\frac{1}{30}$ up to 200 cfs or larger. The smaller flumes are well suited to the requirement of measuring farm water deliveries. The Parshall flume operates successfully with less loss of head than required for weirs.

Silt will not deposit in the structure where it would affect the accuracy because the velocity is higher than that in the channel. Ordinary velocities of approach have little or no effect on the measurement. The flume may be used with recording or registering instruments when continuous records of flow are desired, or with an indicating gage graduated to give the flow in any unit desired.

The Parshall flume cannot readily be combined with a turnout. For free-flow conditions the exit velocity is relatively high, and channel protection is generally necessary downstream from the flume to prevent erosion.

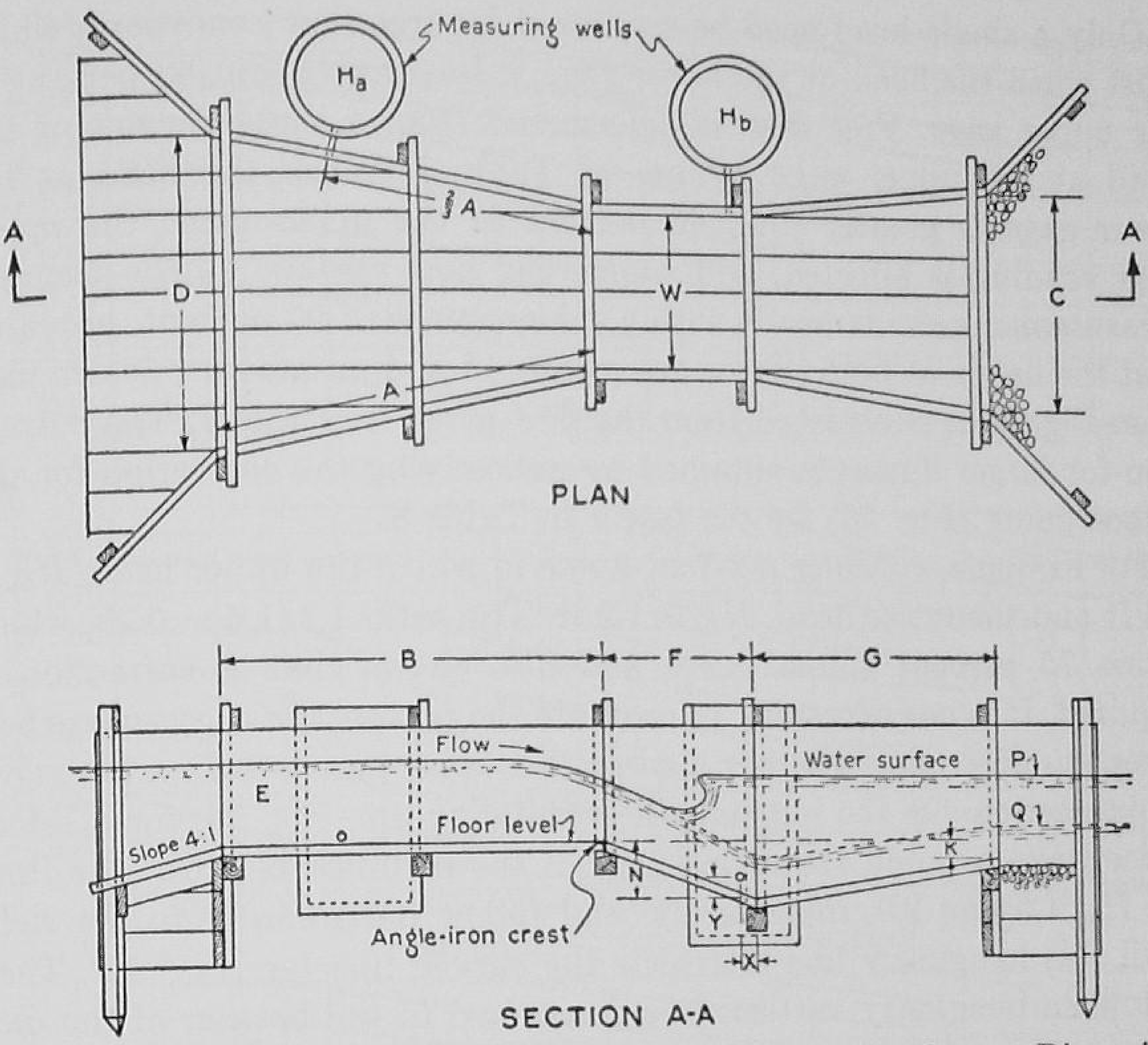

Fig. 22*A*. Plan and longitudinal section of Parshall measuring flume. Dimensions are given in Table 9. (*Calif. Agr. Exp. Sta. Bul.* 588.)

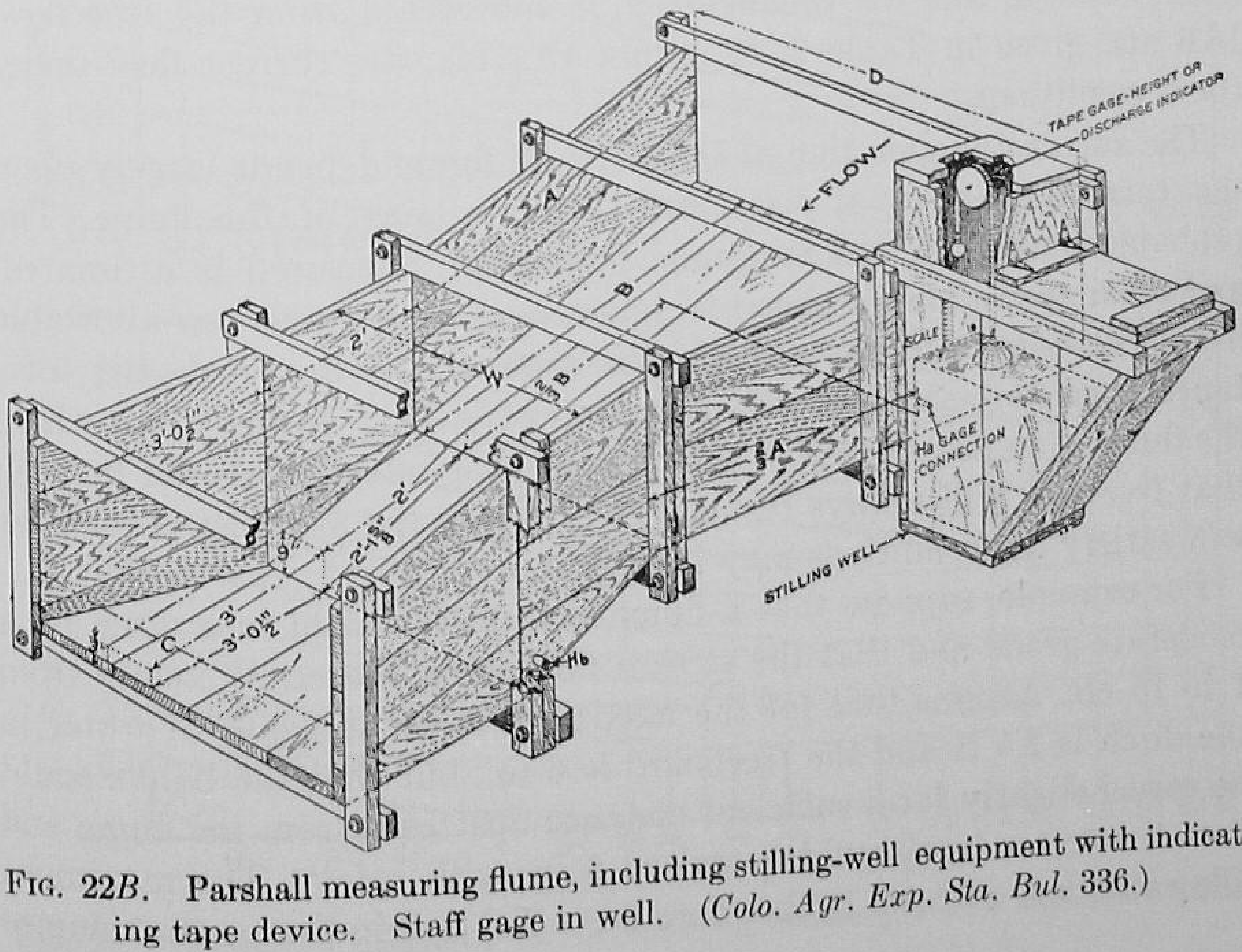

Fig. 22*B*. Parshall measuring flume, including stilling-well equipment with indicating tape device. Staff gage in well. (*Colo. Agr. Exp. Sta. Bul.* 336.)

Only a single head need be measured for free-flow conditions, which exist when the head at the lower gage is less than about 60 percent of the upper gage. Free flow is determined from a measurement of the head at the upper gage by use of Table 7. When the head at the lower gage is greater than 60 percent of the upper gage, the upper gage reading is affected, and submerged flow results. Fairly accurate measurements can be made with a submergence of 90 percent, provided that the heads at both places are measured and an amount determined from Fig. 23 is subtracted from the flow given in Table 7. The correction for larger flumes is obtained by multiplying the correction for the 1-foot flume (Fig. 23) by the factor in Table 8.

For example, consider a 2-foot flume in which the upper head, H_a, is 1.6 ft and the lower head, H_b, is 1.2 ft. The ratio 1.2/1.6 = 0.75, which shows 75 percent submergence and also shows that a correction is required. It is not necessary to compute the percentage of submergence, except to determine whether a correction is necessary—often answered by inspection. On the left margin of the diagram, Fig. 23, for a 1-foot flume, take a point about one-fifth of the distance between the lines for H_a, 1.5 and 2.0, respectively, and follow horizontally to the right until this imaginary line intersects the curved line for $H_b = 1.2$. Then follow an imaginary vertical line downward to the bottom of the diagram and read the correction, which is approximately 0.5 cfs. This amount is now multiplied by the factor 1.8 for a 2-foot flume, obtained from Table 8, and the product, 0.9, is subtracted from the free flow, 16.6 cfs, given in Table 7, to obtain 15.7 cfs, the correct flow under these conditions.

The successful operation of the Parshall flume depends largely upon the correct selection of sizes and proper setting of the flume. The probable maximum and minimum flow to be measured is estimated, and maximum allowable head is determined. The maximum allowable head will depend on the grade of the channel and the freeboard (distance from normal water surface to top of banks) at the place where the flume is to be installed. When possible, the selection should be such that free flow will always result. For economy the smallest flume that will satisfy the conditions may be selected.

For example, suppose that a flume is to be installed in a ditch on a moderate grade and that the stream flow to be measured varies from 1 to 15 cfs. Assume that for the maximum flow the depth of water in the ditch is 2.5 ft and the freeboard is 6 in., but that the banks could be raised slightly for a sufficient distance upstream from the flume and that the water level could be raised 6 in. with safety. The maximum allowable loss of head is therefore 6 in. Table 7 indicates that flumes

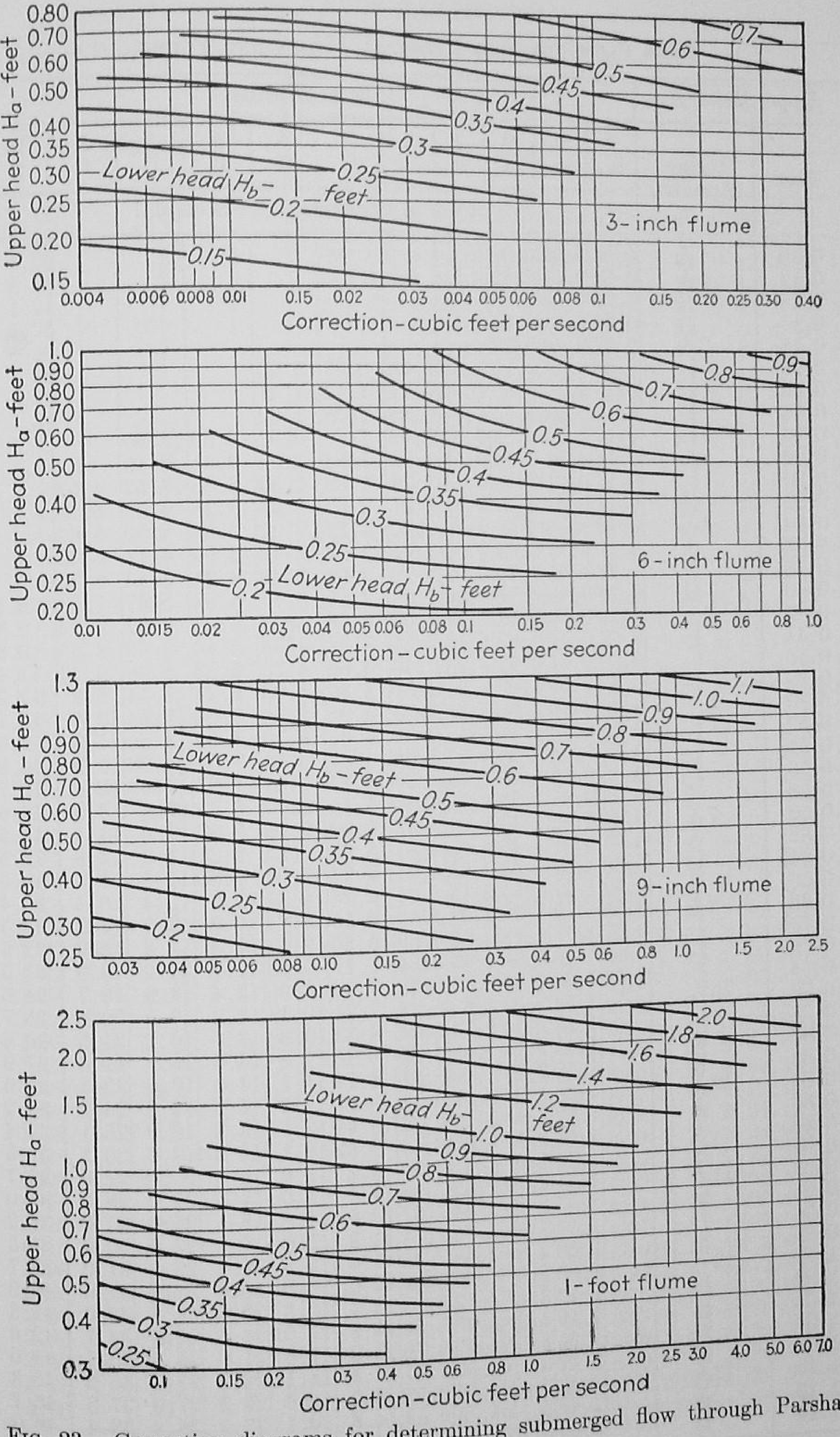

FIG. 23. Correction diagrams for determining submerged flow through Parshall measuring flumes.

TABLE 7

Free Flow through Parshall Measuring Flume

Upper Head, H_a		Throat Widths										
Feet	Inches (Approx.)	3 in.	6. in.	9 in.	1 ft	2 ft	3 ft	4 ft	5 ft	6 ft	8 ft	10 ft
		Flow in Cubic Feet per Second										
0.10	1 3/16	0.03	0.05	0.09								
0.12	1 5/16	0.04	0.07	0.12								
0.14	11/16	0.05	0.09	0.15								
0.16	15/16	0.06	0.11	0.19								
0.18	2 3/16	0.07	0.14	0.22								
0.20	3/8	0.08	0.16	0.26	0.35	0.66	0.97	1.26				
0.22	5/8	0.10	0.19	0.30	0.40	0.77	1.12	1.47				
0.24	7/8	0.11	0.22	0.35	0.46	0.88	1.28	1.69				
0.26	3 1/8	0.12	0.25	0.39	0.51	0.99	1.46	0.91	2.36	2.80		
0.28	3/8	0.14	0.28	0.44	0.58	1.11	1.64	2.15	2.65	3.15		
0.30	5/8	0.15	0.31	0.49	0.64	1.24	1.82	2.39	2.96	3.52	4.62	
0.32	13/16	0.17	0.34	0.54	0.71	1.37	2.02	2.65	3.28	3.90	5.13	
0.34	4 1/16	0.19	0.38	0.59	0.77	1.50	2.22	2.92	3.61	4.30	5.66	
0.36	5/16	0.21	0.41	0.64	0.84	1.64	2.42	3.19	3.95	4.71	6.20	
0.38	9/16	0.22	0.45	0.70	0.92	1.79	2.64	3.48	4.31	5.13	6.76	
0.40	13/16	0.24	0.48	0.76	0.99	1.93	2.86	3.77	4.68	5.57	7.34	9.1
0.42	5 1/16	0.26	0.52	0.81	1.07	2.09	3.08	4.07	5.05	6.02	7.94	9.8
0.44	1/4	0.28	0.56	0.87	1.15	2.24	3.32	4.38	5.43	6.48	8.55	10.6
0.46	1/2	0.30	0.61	0.94	1.23	2.40	3.56	4.70	5.83	6.96	9.19	11.4
0.48	3/4	0.32	0.65	1.00	1.31	2.57	3.80	5.03	6.24	7.44	9.8	12.2
0.50	6	0.34	0.69	1.06	1.39	2.73	4.05	5.36	6.66	7.94	10.5	13.1
0.52	1/4	0.36	0.73	1.13	1.48	2.90	4.31	5.70	7.09	8.46	11.2	13.9
0.54	1/2	0.38	0.78	1.20	1.57	3.08	4.57	6.05	7.52	8.98	11.9	14.8
0.56	3/4	0.40	0.82	1.26	1.66	3.26	4.84	6.41	7.97	9.52	12.6	15.7
0.58	15/16	0.43	0.87	1.33	1.75	3.44	5.11	6.77	8.43	10.1	13.3	16.6
0.60	7 3/16	0.45	0.92	1.40	1.84	3.62	5.39	7.15	8.89	10.6	14.1	17.5
0.62	7/16	0.47	0.97	1.48	1.93	3.81	5.68	7.53	9.37	11.2	14.8	18.5
0.64	11/16	0.50	1.02	1.55	2.03	4.01	5.97	7.91	9.85	11.8	15.6	19.5
0.66	15/16	0.52	1.07	1.63	2.13	4.20	6.26	8.31	10.3	12.4	16.4	20.4
0.68	8 3/16	0.55	1.12	1.70	2.23	4.40	6.56	8.71	10.9	13.0	17.2	21.5
0.70	3/8	0.57	1.17	1.78	2.33	4.60	6.86	9.11	11.4	13.6	18.0	22.5
0.72	5/8	0.60	1.23	1.86	2.43	4.81	7.17	9.53	11.9	14.2	18.9	23.5
0.74	7/8	0.62	1.28	1.94	2.53	5.02	7.49	9.95	12.4	14.9	19.7	24.6
0.76	9 1/8	....	1.34	2.02	2.63	5.23	7.81	10.1	12.9	15.5	20.6	25.7
0.78	3/8	....	1.39	2.10	2.74	5.44	8.13	10.8	13.5	16.2	21.5	26.8
0.80	5/8	....	1.45	2.18	2.85	5.66	8.46	11.3	14.0	16.8	22.4	27.9
0.82	13/16	....	1.50	2.27	2.96	5.88	8.79	11.7	14.6	17.5	23.3	29.0
0.84	10 1/16	....	1.56	2.35	3.07	6.11	9.13	12.2	15.2	18.2	24.2	30.2
0.86	5/16	....	1.62	2.44	3.18	6.33	9.48	12.6	15.8	18.9	25.1	31.4
0.88	9/16	....	1.68	2.52	3.29	6.56	9.82	13.1	16.3	19.6	26.1	32.5
0.90	13/16	....	1.74	2.61	3.41	6.80	10.2	13.6	16.9	20.3	27.0	33.7
0.92	11 1/16	....	1.81	2.70	3.52	7.03	10.5	14.0	17.5	21.0	28.0	35.0
0.94	1/4	....	1.87	2.79	3.64	7.27	10.9	14.5	18.1	21.8	29.0	36.2
0.96	1/2	....	1.93	2.88	3.76	7.51	11.3	15.0	18.8	22.5	30.0	37.5
0.98	3/4	....	2.00	2.98	3.88	7.75	11.6	15.5	19.4	23.2	31.0	38.7
1.00	12	....	2.06	3.07	4.00	8.00	12.0	16.0	20.0	24.0	32.0	40.0
1.02	1/4	....	2.12	3.17	4.12	8.25	12.4	16.5	20.6	24.8	33.0	41.3
1.04	1/2	....	2.19	3.26	4.25	8.50	12.8	17.0	21.3	25.6	34.1	42.6
1.06	3/4	....	2.26	3.36	4.37	8.76	13.2	17.5	21.9	26.3	35.1	44.0
1.08	15/16	....	2.32	3.45	4.50	9.01	13.5	18.1	22.6	27.1	36.2	45.3
1.10	13 3/16	....	2.40	3.55	4.62	9.27	13.9	18.6	23.3	27.9	37.3	46.7
1.12	7/16	....	2.46	3.65	4.75	9.54	14.3	19.1	23.9	28.8	38.4	48.0
1.14	11/16	....	2.53	3.75	4.88	9.80	14.7	19.7	24.6	29.6	39.5	49.4

TABLE 7 (*Concluded*)

Upper Head, H_a		Throat Widths										
Feet	Inches (Approx.)	3 in.	6 in.	9 in.	1 ft	2 ft	3 ft	4 ft	5 ft	6 ft	8 ft	10 ft
		Flow in Cubic Feet per Second										
1.16	$13\frac{15}{16}$	....	2.60	3.85	5.01	10.1	15.1	20.2	25.3	30.4	40.6	50.8
1.18	$14\frac{3}{16}$	....	2.68	3.95	5.15	10.3	15.6	20.8	26.0	31.3	41.8	52.3
1.20	$\frac{3}{8}$	....	2.75	4.06	5.28	10.6	16.0	21.3	26.7	32.1	42.9	53.7
1.22	$\frac{5}{8}$	....	2.82	4.16	5.41	10.9	16.4	21.9	27.4	33.0	44.1	55.2
1.24	$\frac{7}{8}$	....	2.89	4.27	5.55	11.2	16.8	22.5	28.1	33.8	45.2	56.6
1.26	$15\frac{1}{8}$	....	....	4.37	5.69	11.5	17.2	23.0	28.9	34.7	46.4	58.1
1.28	$\frac{3}{8}$	....	....	4.48	5.82	11.7	17.7	23.6	29.6	35.6	47.6	59.6
1.30	$\frac{5}{8}$	....	....	4.59	5.96	12.0	18.1	24.2	30.3	36.5	48.8	61.1
1.32	$\frac{13}{16}$	....	....	4.69	6.10	12.3	18.5	24.8	31.1	37.4	50.0	62.7
1.34	$16\frac{1}{16}$	....	....	4.80	6.25	12.6	19.0	25.4	31.8	38.3	51.2	64.2
1.36	$\frac{5}{16}$	....	....	4.92	6.39	12.9	19.4	26.0	32.6	39.2	52.5	65.7
1.38	$\frac{9}{16}$	....	....	5.03	6.53	13.2	19.9	26.6	33.3	40.1	53.7	67.3
1.40	$\frac{13}{16}$	....	....	....	6.68	13.5	20.3	27.2	34.1	41.1	55.0	68.9
1.42	$17\frac{1}{16}$	....	....	....	6.82	13.8	20.8	27.8	34.9	42.0	56.2	70.5
1.44	$\frac{1}{4}$	....	....	....	6.97	14.1	21.2	28.5	35.7	42.9	57.5	72.1
1.46	$\frac{1}{2}$	....	....	....	7.12	14.4	21.7	29.1	36.5	43.9	58.8	73.7
1.48	$\frac{3}{4}$	....	....	....	7.26	14.7	22.2	29.7	37.3	44.9	60.1	75.4
1.50	18	....	....	....	7.41	15.0	22.6	30.3	38.1	45.8	61.4	77.0
1.52	$\frac{1}{4}$	....	....	....	7.57	15.3	23.1	31.0	38.9	46.8	62.7	78.7
1.54	$\frac{1}{2}$	....	....	....	7.72	15.6	23.6	31.6	39.7	47.8	64.0	80.4
1.56	$\frac{3}{4}$	....	....	....	7.87	15.9	24.1	32.3	40.5	48.8	65.4	82.1
1.58	$\frac{15}{16}$	....	....	....	8.02	16.3	24.6	32.9	41.4	49.8	66.7	83.8
1.60	$19\frac{3}{16}$	....	....	....	8.18	16.6	25.1	33.6	42.2	50.8	68.1	85.5
1.62	$\frac{7}{16}$	....	....	....	8.34	16.9	25.5	34.3	43.0	51.8	69.5	87.2
1.64	$\frac{11}{16}$	....	....	....	8.49	17.2	26.0	34.9	43.9	52.8	70.9	89.0
1.66	$\frac{15}{16}$	....	....	....	8.65	17.6	26.5	35.6	44.7	53.9	72.3	90.7
1.68	$20\frac{3}{16}$	....	....	....	8.81	17.9	27.0	36.3	45.6	54.9	73.7	92.5
1.70	$\frac{3}{8}$	....	....	....	8.97	18.2	27.6	37.0	46.4	56.0	75.1	94.3
1.72	$\frac{5}{8}$	....	....	....	9.13	18.5	28.1	37.7	47.3	57.0	76.5	96.1
1.74	$\frac{7}{8}$	....	....	....	9.29	18.9	28.6	38.3	48.2	58.1	77.9	97.9
1.76	$21\frac{1}{8}$	....	....	....	9.46	19.2	29.1	39.0	49.1	59.1	79.4	99.7
1.78	$\frac{3}{8}$	....	....	....	9.62	19.6	29.6	39.7	49.9	60.2	80.8	101.4
1.80	$\frac{5}{8}$	....	....	....	9.79	19.9	30.1	40.5	50.8	61.3	82.3	103.4
1.82	$\frac{13}{16}$	....	....	....	9.95	20.2	30.7	41.2	51.7	62.4	83.8	105.3
1.84	$22\frac{1}{16}$	....	....	....	10.1	20.6	31.2	41.9	52.6	63.5	85.3	107.1
1.86	$\frac{5}{16}$	....	....	....	10.3	20.9	31.7	42.6	53.6	64.6	86.8	109.0
1.88	$\frac{9}{16}$	....	....	....	10.5	21.3	32.3	43.3	54.5	65.7	88.3	110.9
1.90	$\frac{13}{16}$	....	....	....	10.6	21.6	32.8	44.1	55.4	66.8	89.8	112.9
1.92	$23\frac{1}{16}$	....	....	....	10.8	22.0	33.3	44.8	56.3	67.9	91.3	114.8
1.94	$\frac{1}{4}$	....	....	....	11.0	22.4	33.9	45.5	57.3	69.1	92.8	116.7
1.96	$\frac{1}{2}$	....	....	....	11.1	22.7	34.4	46.3	58.2	70.2	94.4	118.7
1.98	$\frac{3}{4}$	....	....	....	11.3	23.1	35.0	47.0	59.1	71.4	95.9	120.6
2.00	24	....	....	....	11.5	23.4	35.5	47.8	60.1	72.5	97.5	122.6
2.05	$\frac{5}{8}$	....	....	....	11.9	24.3	36.9	49.7	62.5	75.4	101.4	127.6
2.10	$25\frac{3}{16}$	....	....	....	12.4	25.3	38.4	51.6	64.9	78.4	105.4	132.7
2.15	$\frac{13}{16}$	....	....	....	12.8	26.2	39.8	53.5	67.4	81.4	109.5	137.8
2.20	$26\frac{3}{8}$	....	....	....	13.3	27.2	41.3	55.5	69.9	84.4	113.6	143.0
2.25	27	....	....	....	13.7	28.1	42.7	57.5	72.4	87.5	117.8	148.3
2.30	$\frac{5}{8}$	....	....	....	14.2	29.1	44.2	59.6	75.0	90.6	122.0	153.7
2.35	$28\frac{3}{16}$	....	....	....	14.7	30.1	45.7	61.6	77.6	93.8	126.0	159.1
2.40	$\frac{13}{16}$	....	....	....	15.2	31.1	47.3	63.7	80.3	97.0	130.7	164.6
2.45	$29\frac{3}{8}$	....	....	....	15.6	32.1	48.8	65.8	82.9	100.2	135.1	170.2
2.50	30	....	....	....	16.1	33.1	50.4	67.9	85.6	103.5	139.5	175.8

with a throat width of 1, 2, or 3 ft could measure the entire range of flow. For a flow of 15 cfs, the head, H_a, would be 2.38 ft for a 1-foot flume, 1.50 for a 2-foot flume, and 1.16 for a 3-foot flume.

For free flow, submergence should not exceed 60 percent, so that the loss of head should not be less than 40 percent of the head, H_a. The required loss for the 1-foot flume would be $0.4 \times 2.38 = 0.95$ ft; for the 2-foot flume $0.4 \times 1.50 = 0.60$ ft; and for the 3-foot flume, $0.4 \times 1.16 = 0.46$ ft. The 3-foot flume is, therefore, the smallest size for which the maximum loss of head will be less than 6 in.

TABLE 8

FACTORS M TO BE USED IN CONNECTION WITH FIG. 13 FOR DETERMINING SUBMERGED DISCHARGES FOR PARSHALL MEASURING FLUMES LARGER THAN 1-FOOT THROAT WIDTH*

Throat Width, W, in Feet	Factor, M	Throat Width, W, in Feet	Factor, M
1	1.0	5	3.7
2	1.8	6	4.3
3	2.4	7	4.9
4	3.1	8	5.4

* These factors are to be multiplied by the correction obtained from Fig. 23 and subtracted from the free flow for the same upper head, H_a, Table 7, to determine flow for submerged conditions. Computed from the expression $M = W^{0.815}$.

The required depth upstream for the 3-foot flume is $2.50 + 0.46 = 2.96$ ft; and the head, H_a, for 15 cfs is 1.16 ft. The crest should be set $2.96 - 1.16 = 1.8$ ft above the bottom of the ditch. If the 2-foot flume is selected, the depth upstream will be $2.50 + 0.60 = 3.10$ ft; and since the head, H_a, in this case is 1.50, the elevation of the crest should be $3.10 - 1.50 = 1.60$ ft above the bottom of the ditch. In order to use the 2-foot flume, one would have to raise the ditch banks higher than assumed or permit a maximum submergence of about 67 percent, in which case the crest could be set 1.5 ft above the bottom of the ditch. Had the available loss of head been sufficient to permit the use of a 1-foot flume, the upstream depth would be 3.45 ft. The crest would then be set $3.45 - 2.38 = 1.07$ ft above the bottom of the ditch. The greater the throat width, the higher the crest must be set to insure free-flow operation.

Parshall flumes may be built of wood, concrete, or, in the smaller sizes, of heavy sheet metal. The dimensions of flumes ranging from 3 in. to 10 ft in throat width are given in Tables 9 and 10.

To secure accuracy in measurement these flumes must be built to exact dimensions, especially the converging and throat sections. The flow of the upstream converging section, especially the crest, must be

TABLE 9

STANDARD DIMENSIONS OF PARSHALL MEASURING FLUMES FROM 3 TO 9 INCHES THROAT WIDTH

Dimension Letter*	Dimensions in Feet and Inches for Throat Widths (*W*) of 3 in.	6 in.	9 in.
A	1′ 6$\frac{3}{8}$″	2′ $\frac{7}{16}$″	2′ 10$\frac{5}{8}$″
2/3 *A*	1′ $\frac{1}{4}$″	1′ 4$\frac{5}{16}$″	1′ 11$\frac{1}{8}$″
B	1′ 6″	2′ 0″	2′ 10″
2/3 *B*	1′ 0″	1′ 4″	1′ 10$\frac{5}{8}$″
C	0′ 7″	1′ 3$\frac{1}{2}$″	1′ 3″
D	0′ 10$\frac{3}{16}$″	1′ 3$\frac{1}{2}$″	1′ 10$\frac{5}{8}$″
E	1′ 3″	1′ 6″	2′ 0″
F	0′ 6″	1′ 0″	1′ 0″
G	1′ 0″	2′ 0″	1′ 6″
K	0′ 1″	0′ 3″	0′ 3″
N	0′ 2$\frac{1}{4}$″	0′ 4$\frac{1}{2}$″	0′ 4$\frac{1}{2}$″
X	0′ 1″	0′ 2″	0′ 2″
Y	0′ 1$\frac{1}{2}$″	0′ 3″	0′ 3″

* Letters refer to Fig. 22*A*.

level. Wing walls should be provided at both ends, and those on upstream should be placed at an angle of 45° with the center. Where the flume is more than 6 in. above the channel bottom a short inclined floor should be provided.

TABLE 10

STANDARD DIMENSIONS OF PARSHALL MEASURING FLUMES FROM 1 TO 10 FEET THROAT WIDTH

Throat Width, *W*, in feet	Dimensions in Feet and Inches* *A*	2/3 *A*	*B*	2/3 *B*	*C*	*D*
1.0	4′ 6″	3′ 0″	4′ 4$\frac{7}{8}$″	2′ 11$\frac{1}{4}$″	2′ 0″	2′ 9$\frac{1}{4}$″
2.0	5′ 0″	3′ 4″	4′ 10$\frac{7}{8}$″	3′ 3$\frac{1}{4}$″	3′ 0″	3′ 11$\frac{1}{2}$″
3.0	5′ 6″	3′ 8″	5′ 4$\frac{3}{4}$″	3′ 7$\frac{1}{8}$″	4′ 0″	5′ 1$\frac{7}{8}$″
4.0	6′ 0″	4′ 0″	5′ 10$\frac{5}{8}$″	3′ 11$\frac{1}{8}$″	5′ 0″	6′ 4$\frac{1}{4}$″
5.0	6′ 6″	4′ 4″	6′ 4$\frac{1}{2}$″	4′ 3″	6′ 0″	7′ 6$\frac{5}{8}$″
6.0	7′ 0″	4′ 8″	6′ 10$\frac{3}{8}$″	4′ 6$\frac{7}{8}$″	7′ 0″	8′ 9″
7.0	7′ 6″	5′ 0″	7′ 4$\frac{1}{4}$″	4′ 10$\frac{7}{8}$″	8′ 0″	9′ 11$\frac{3}{8}$″
8.0	8′ 0″	5′ 4″	7′ 10$\frac{1}{8}$″	5′ 2$\frac{3}{4}$″	9′ 0″	11′ 1$\frac{3}{4}$″
10.0	9′ 0″	6′ 0″	8′ 9$\frac{7}{8}$″	5′ 10$\frac{5}{8}$″	11′ 0″	13′ 6$\frac{3}{8}$″

* Letters refer to Fig. 22*B*, in which other dimensions for these flumes are shown.

29. The Current Meter A device widely used by engineers for measuring flowing water is the current meter, one type of which is shown in Fig. 24*A*. Another meter is shown under the water in Fig. 24*B* in the position of actual use. The meter is calibrated by passing it through still water at a known speed and noting the number of revolutions per second. When the calibrated meter is held still in running water at the proper depth, it is thus possible to determine the average velocity of the water by observing the number of revolutions per second in the meter. It has

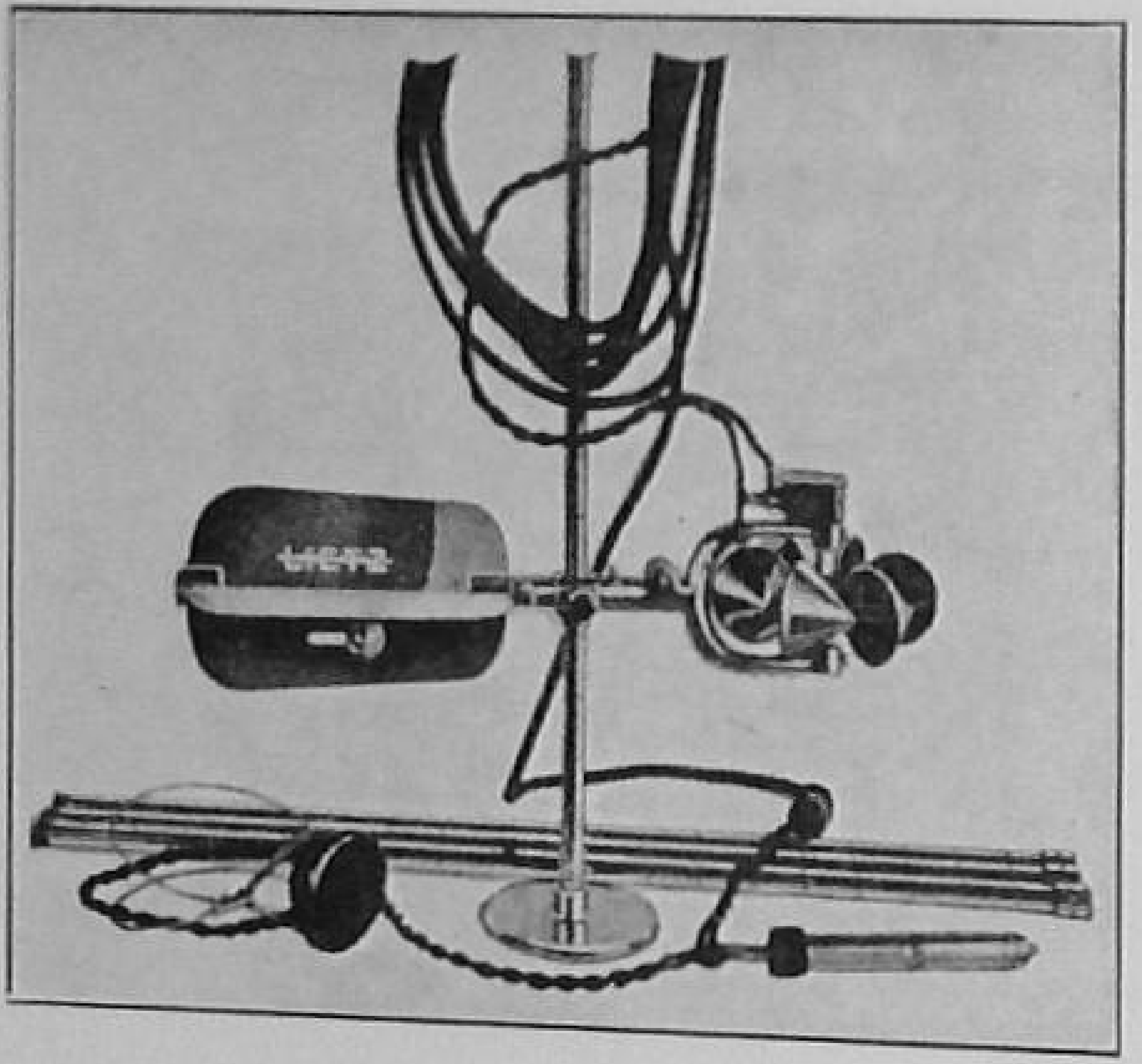

Fig. 24*A*. Current meter showing rod suspension with double-end hanger and round wading base. (The A. Leitz Company.)

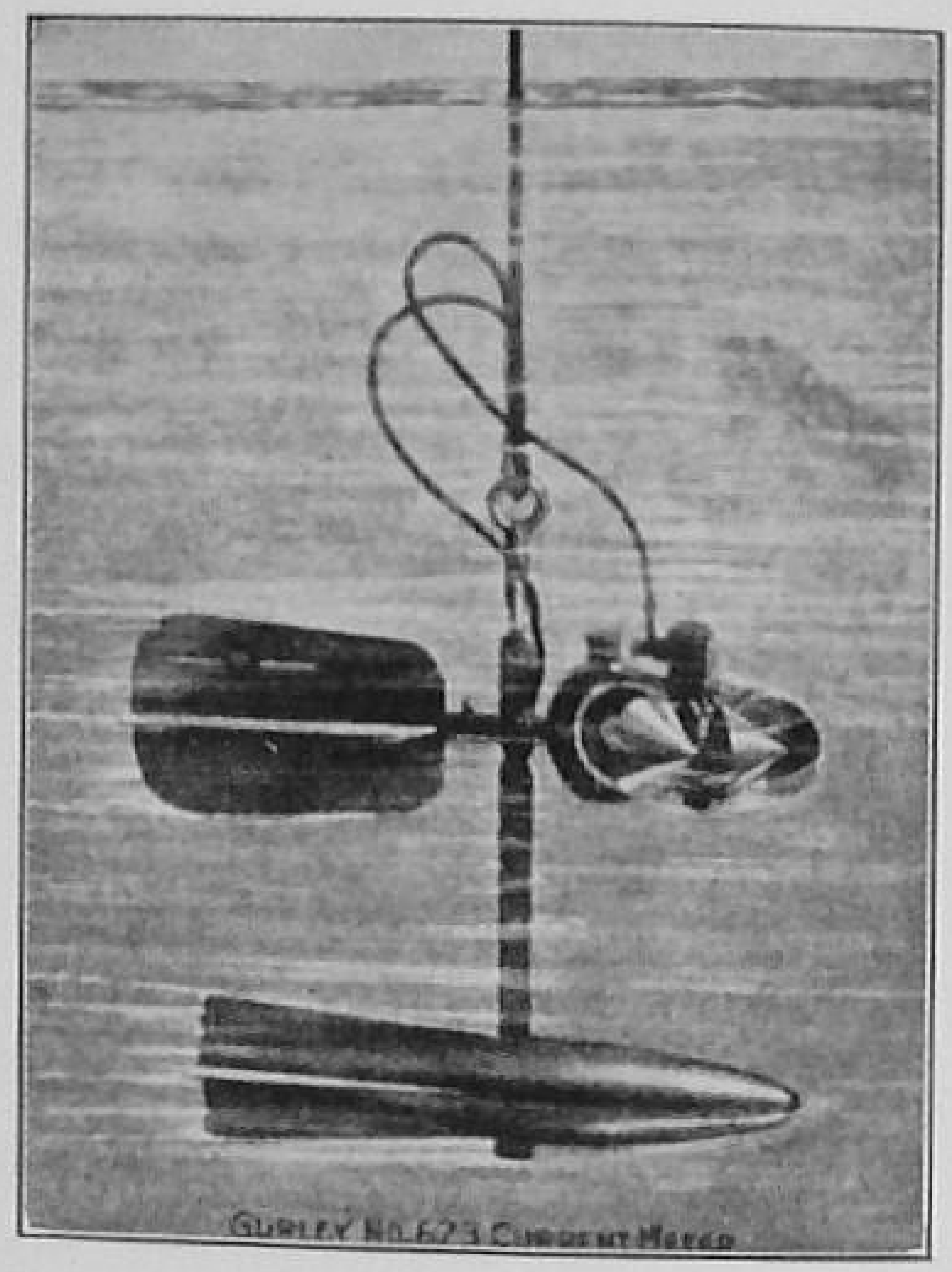

Fig. 24*B*. Gurley current meter in use.

been found in streams not over 1.5 ft in depth that the average velocity is at about 0.6 of the depth;* in streams over 1.5 ft in depth that the average velocity is represented by the average of the velocities at 0.2 and 0.8 of the depth. In the measurement of flowing water it is essential that the current meter be placed at the point or points of average velocity. Another method of determining the average velocity in a stream is the integration method, in which the current meter is raised and lowered slowly and at a constant rate from the bottom to the top of the stream. On practically all the larger canals, and on rivers, discharge measurements are computed from current-meter readings of velocity and measured cross-section areas.

By measuring the discharge of a canal or river at several different

* Some authorities have found that velocities measured at 0.6 of the depth in shallow streams usually range from 4 to 6 percent higher than the true average velocities.

stages (or depths) the engineer obtains data from which he determines a relation between the depth of the water and the discharge of the stream. The changes in depth are usually referred to a permanent bench mark, or elevation datum; and distances vertically above datum are designated "gage heights." After measuring the discharges at various gage heights the engineer plots a rating curve, of which Fig. 25 is typical. This figure shows discharges ranging from zero cfs at 0.4 ft gage height to 100 cfs at a gage height of 2.35 ft. At any

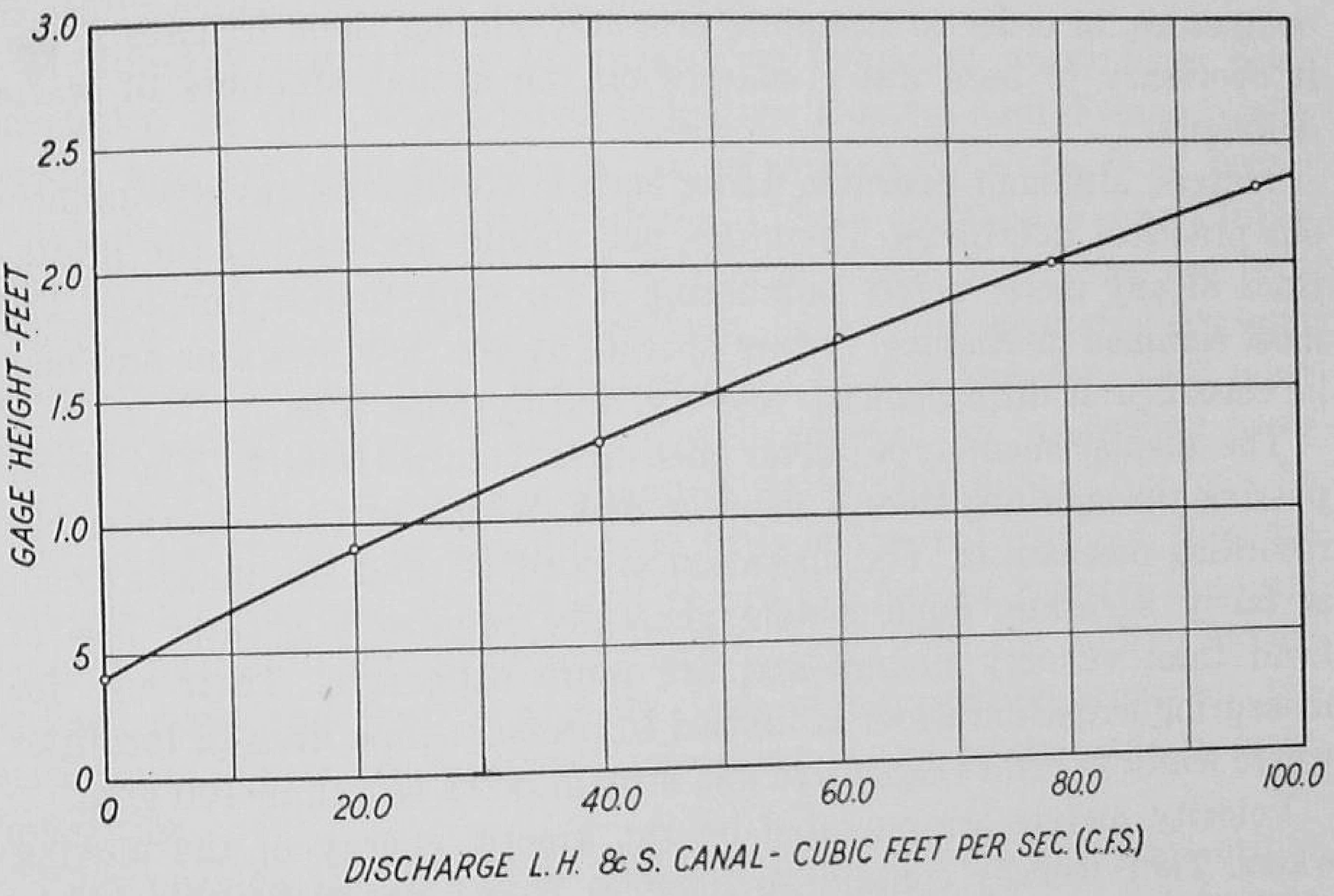

FIG. 25. Typical rating curve for an irrigation canal.

gage heights between these limits the reader can determine the discharge from the figure. At a gage height of 1 ft, for example, the discharge is 25 cfs.

The major advantages of current meters are that they require no obstruction of stream flow and are suited to large streams. Water commissioners whose responsibility it is to distribute the public waters to those entitled to their use depend very largely on rating curves for their measurements. The gage height may be read by non-technical men, but the actual use of the meter and the making of rating tables and rating curves are tasks for the trained and experienced hydrographer or for an engineer.

30. Mechanical Measuring and Recording Devices A number of mechanical devices for water measurement have been designed, most of

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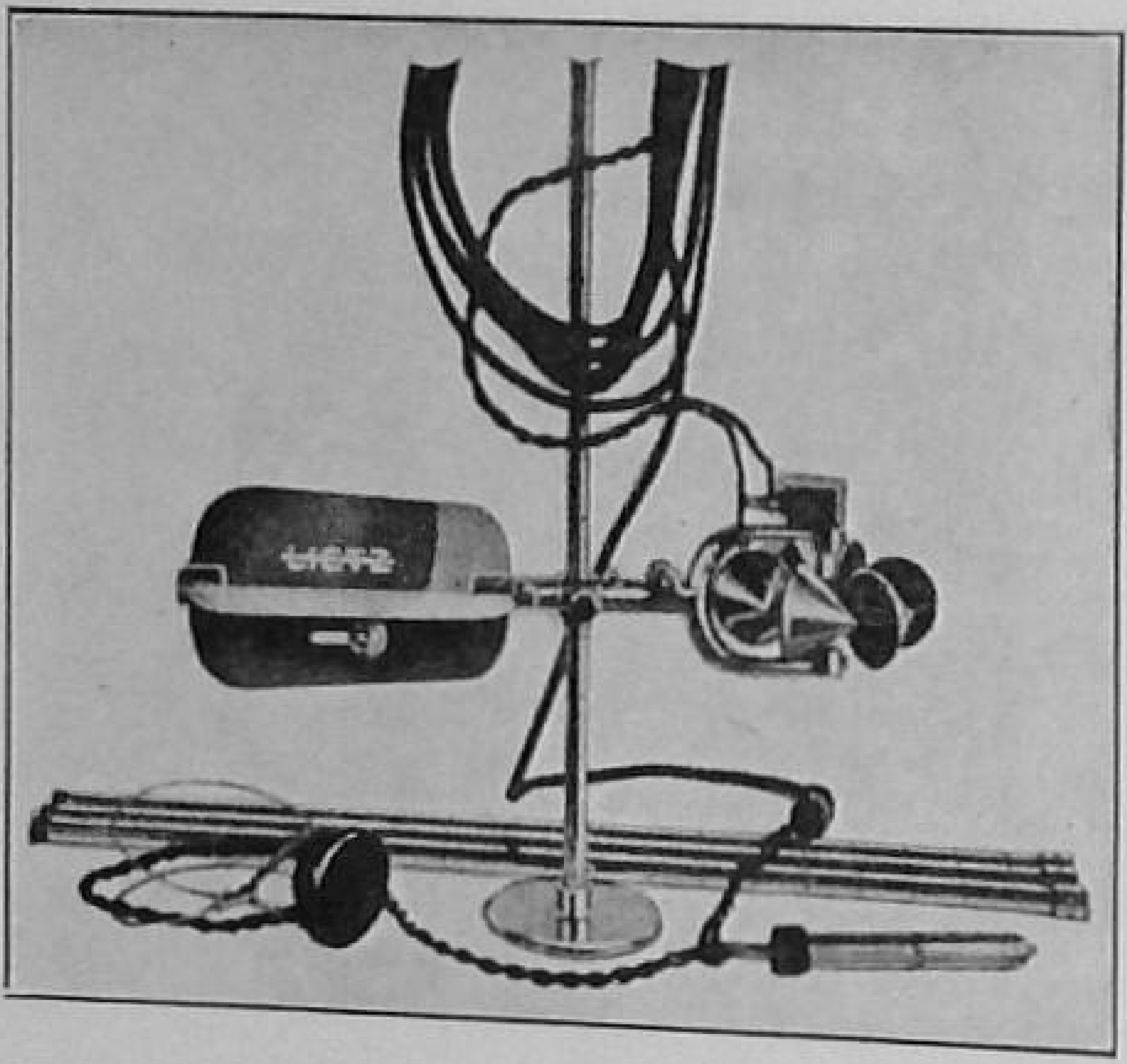
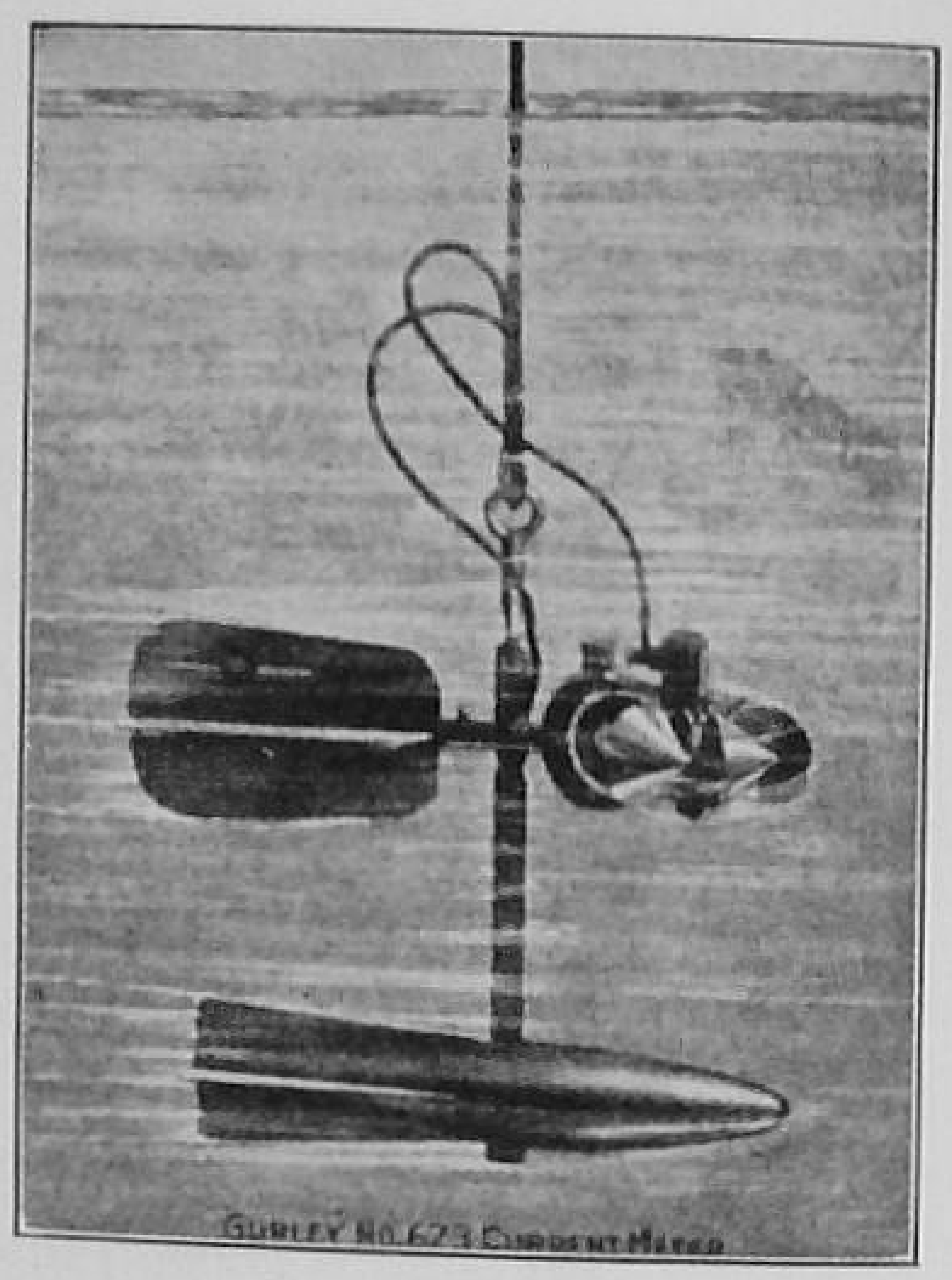


FIG. 24*A*. Current meter showing rod suspension with double-end hanger and round wading base. (The A. Leitz Company.)



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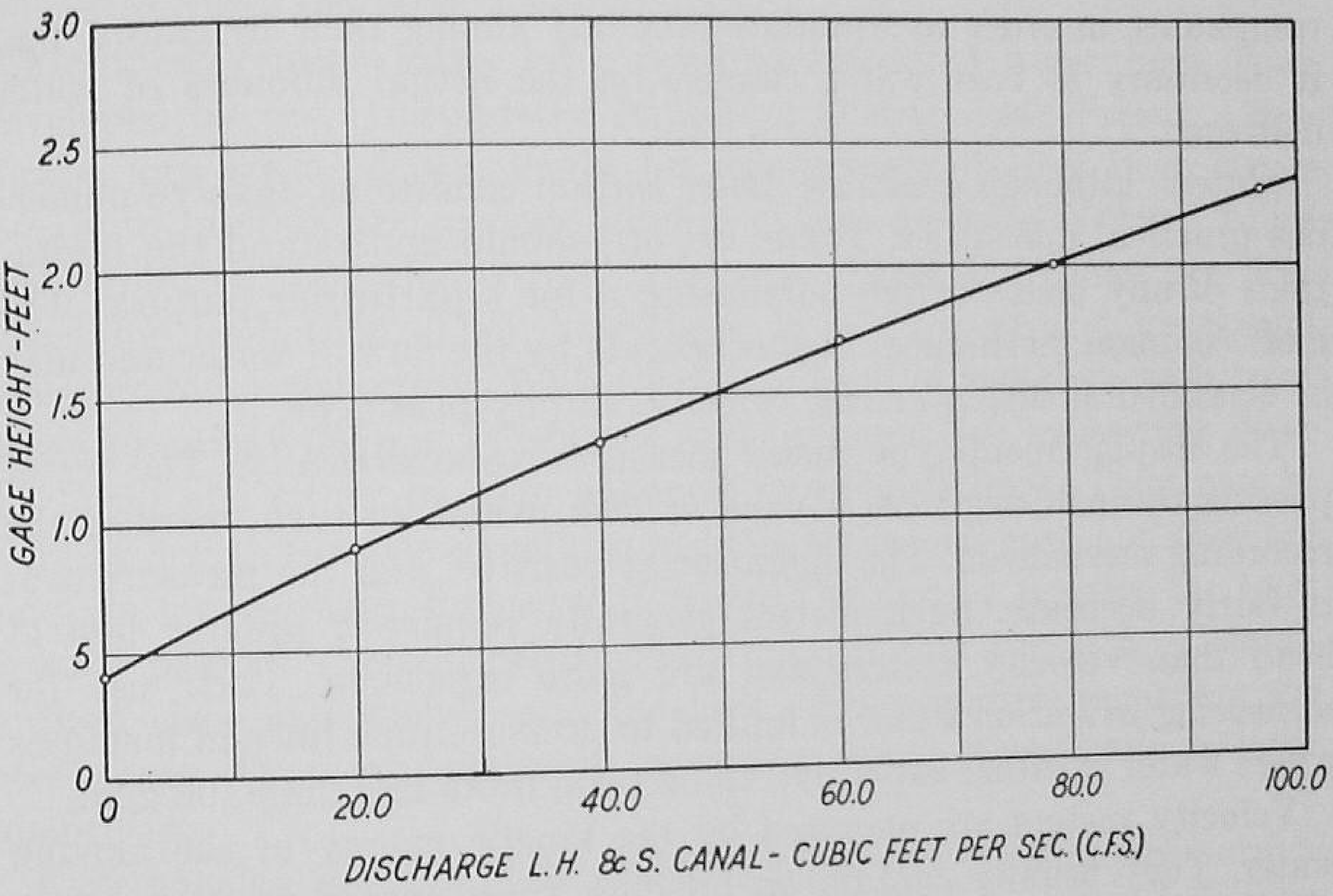

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30. Mechanical Measuring and Recording Devices A number of mechanical devices for water measurement have been designed, most of

which measure the rate of flow, and also automatically register the total amount of water passing in any given period of time. Canal companies that base water charges on the number of acre-feet delivered to individual irrigators find self-recording devices serviceable and convenient.

Important among the devices used to date are the following: Dethridge meter, Hill meter, Venturi meter, and Reliance meter. It is likely that more extended use of mechanical-automatic registering devices will be made as water increases in value and more irrigation companies, in order to stimulate economy among their irrigators, find it necessary to base water charges on the actual amounts of water delivered.

Meters, although desirable under certain conditions, involve numerous practical difficulties. Therefore, one should understand the limitations of any meter before purchasing it for a particular purpose. The most common mechanical meters operate by the flow of water and may be classified as displacement, velocity, and by-pass type.

The displacement-type meter measures volumetrically. The water passing through displaces a vane or disk, which in turn operates the recording mechanism. The operation is positive, and the measurement is fairly accurate. Such meters generally require a greater loss of head than velocity meters and are more expensive. Their use for measuring irrigation water is limited to pressure pipe lines in localities where water is rather expensive and stream flows less than 100 gpm.

Velocity meters are operated by the kinetic energy of the moving water. They usually contain an impeller vane, turned by the water; and their operation is similar to that of a current meter. For high velocities, the impeller vane rotates at a rate almost directly proportional to the velocity of water; for low velocity it may turn more slowly, and below certain velocities it may not move at all. Velocity meters are less expensive and can accommodate larger flows than displacement meters.

The by-pass meter operates differently from either velocity or displacement meters. Only a small part of the flow passes through the registering element, but the meter is calibrated to register the volume that passes. It is used with some other device, such as a weir or orifice, and has somewhat the same characteristics as the velocity meter, since the percentage of water passing through it is not constant but usually varies slightly with the flow.

Mechanical meters have the advantage of eliminating computations in volume determination. This convenience often justifies the expense involved. Meters which are subject to clogging should never be used

on pipe lines receiving water from open ditches unless the entrances are adequately screened to keep out debris.

31. Venturi Tubes and Similar Devices The Venturi tube is a convergent-divergent tube which has been used extensively for measuring flow in pipe lines of diameters ranging from a few inches to several feet, but it has been used only to a limited extent for irrigation water. The standard Venturi tube has been considered too expensive for irrigation purposes. Their proportions are not entirely suited and generally cause too large a loss of head.

Modified Venturi tubes for measuring irrigation water have been developed by the Consolidated Irrigation District near Fresno, California, and are used principally for measuring deliveries from larger canals to laterals and private ditches. These modified Venturi tubes are calibrated individually, and discharge charts and tables are provided for each tube. They have been in use for several years and have proved satisfactory. With them less head is lost than with most other practical devices. They are well adapted for measuring flows up to 50 cfs, either in open channels or in pipe lines. They can be combined with turnout structures at little additional cost, and they are suitable for use with devices that record the flow or register the total volume passed. Their principal disadvantages are: the lack of standardized sizes and shapes, and the lack of information regarding the coefficients. They are relatively expensive except when made in large quantities.

Flow nozzles, the thin plate orifice in pipes and the thin plate orifice on the end of a pipe, have been little used for measuring irrigation water, but they have been utilized somewhat by pump manufacturers and laboratories for testing pumps. The principles underlying the use of these devices are the same as for a Venturi tube. A modified flow nozzle has been developed by Fresno Irrigation District for use in connection with turnout structures to farms.

32. Collins Flow Gage The Collins flow gage is used to measure the flow of water in pipe lines, especially from pumping plants. This device consists essentially of two parts: an impact tube (a special form of Pitot tube) and a water-air manometer. The impact tube, a straight small-diameter brass tube inserted through the pipe, is divided by a partition at the center into two compartments, each containing a small orifice—an impact orifice on the upstream side and a trailing orifice on the downstream side. The differential head is twice the velocity head. Hose connections are made from the ends of the tube to the manometer, the scale of which is so graduated that it indicates the

velocity of the pipe directly in feet per second. Diagrams are furnished for converting to any desired unit of measurement for various pipe diameters.

The velocity of flow through pipes is sometimes determined by measuring the time required for a color or salt to pass through a measured length of pipe.

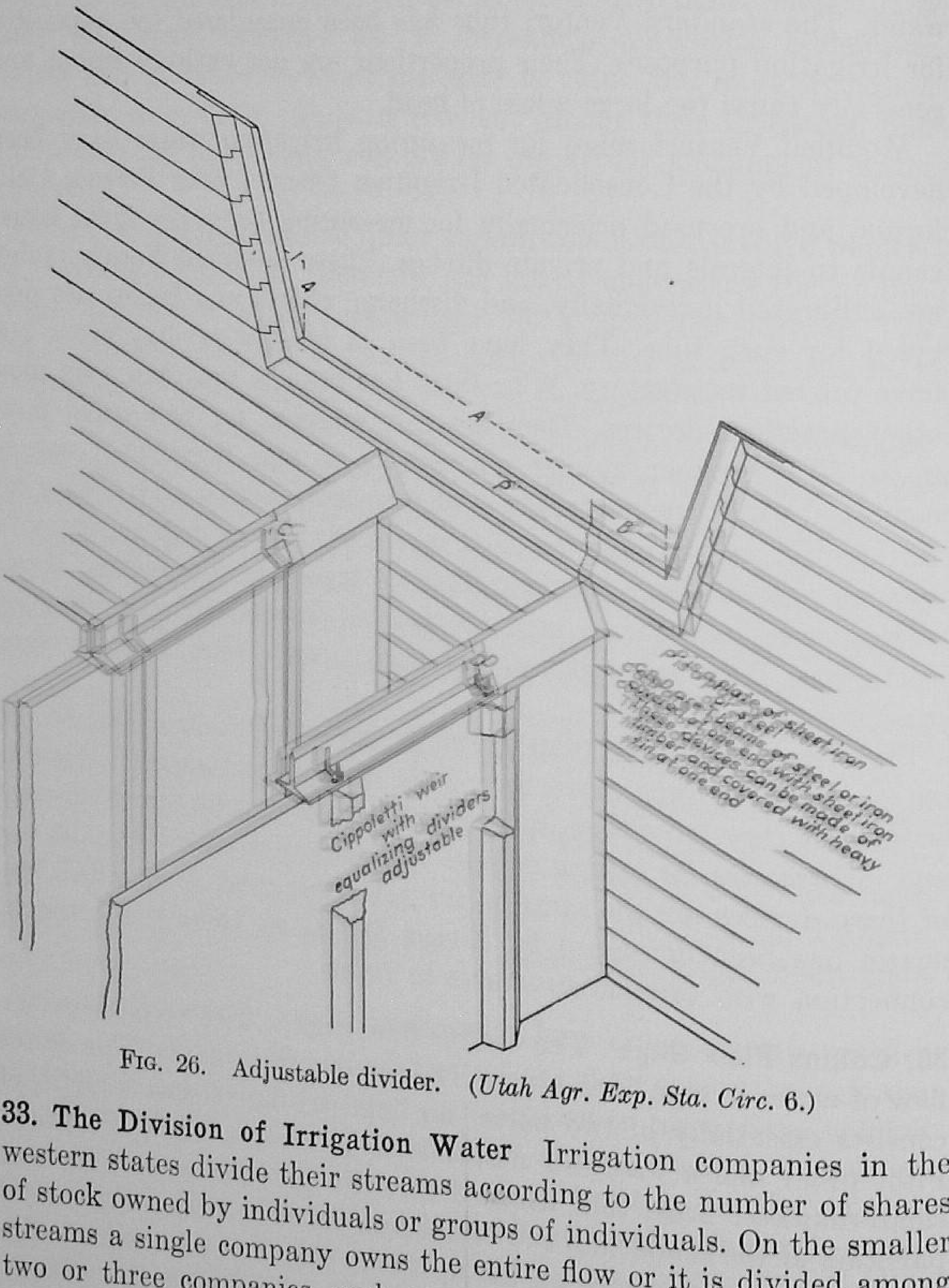


FIG. 26. Adjustable divider. (*Utah Agr. Exp. Sta. Circ.* 6.)

33. The Division of Irrigation Water Irrigation companies in the western states divide their streams according to the number of shares of stock owned by individuals or groups of individuals. On the smaller streams a single company owns the entire flow or it is divided among two or three companies, each company owning a share of the total stream. Some users are less interested in the measurement of the water than in the division of the stream. For example, one company

may be entitled to five-twelfths of the stream and another company to seven-twelfths. Many times a division must be made where it is impracticable to make a measurement.

For satisfactory division, a few principles must be observed. The water must approach the divider in parallel paths; i.e., there must be no cross currents. To secure this condition the divider box must be placed at the lower end of a long flume or straight open channel. The floor of the channel immediately above the divider should be level transversely. If the water is reasonably free from silt it is desirable

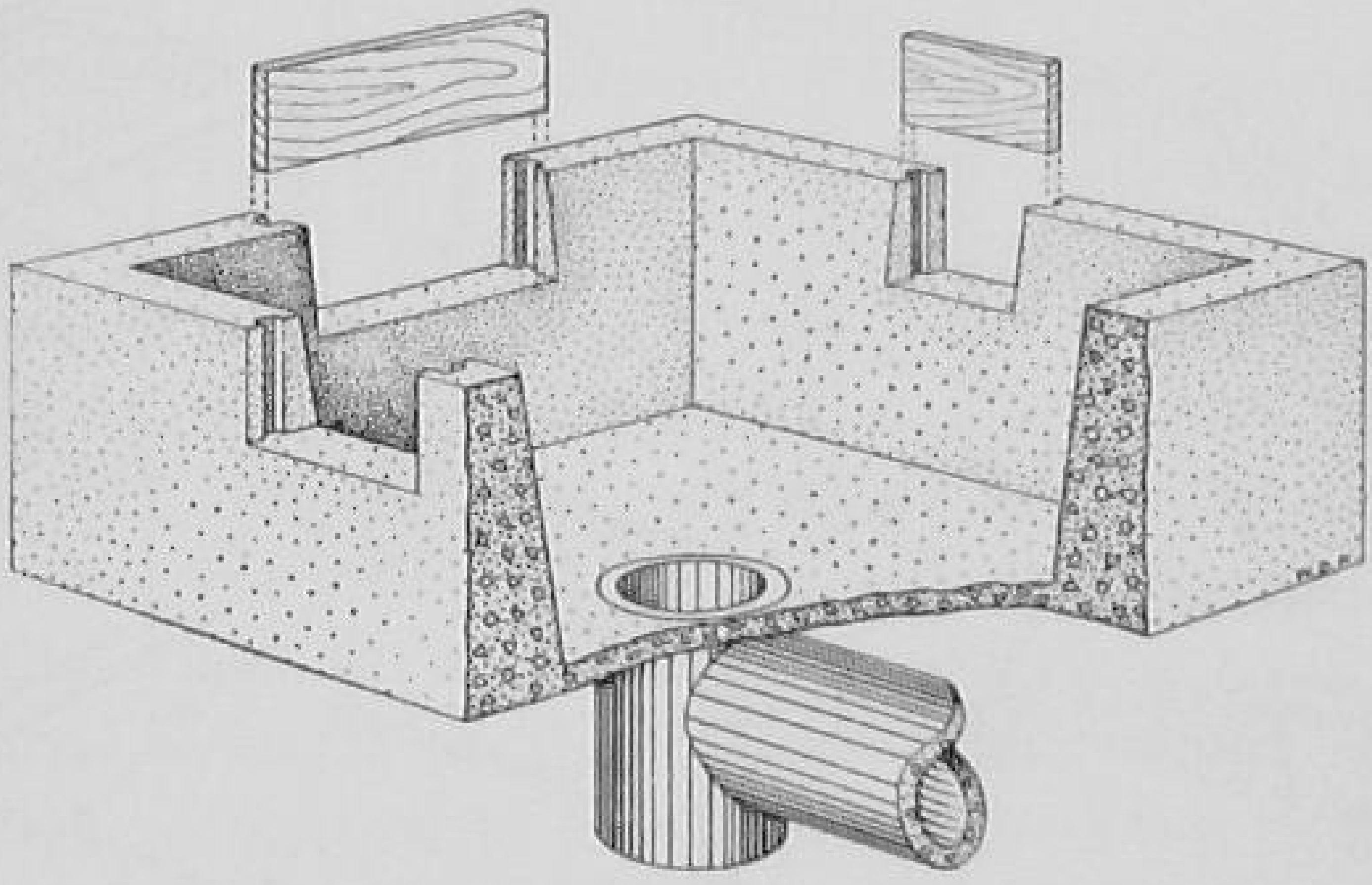


FIG. 27. Proportional division box. (*U.S.D.A. Farmers' Bul.* 348.)

to have it approach the divider at a low velocity. For streams carrying considerable silt and gravel there should be no obstruction in the channel in the form of a bulkhead, and the velocity with which the water enters should be maintained through the structure. It is very important that divider structures have a long, straight channel of approach. Any gravel or debris allowed to collect in the channel of approach will cause cross currents and interfere with proper division.

The flow over a weir can be easily divided by placing a sharp-edged partition below the weir to divide the stream as it falls over the crest. The crest of this partition should be placed a sufficient distance below the weir crest to permit a free circulation of air between the divider and the sheet of water falling over the weir.

The discharge over a weir is not exactly proportional to the length of the crest; the error in considering it so is slight for the lower heads. The trapezoidal weir is the most desirable type as a divider. The flow over this weir is very nearly proportional to length of crest. If it is desired to divide the stream into two parts, one taking five-sixths and the other one-sixth of the flow, the divider should be placed one-sixth of the distance from the end of the weir. Figure 26 shows a trapezoidal weir divider fixed to divide a stream into three parts.

If it is desired to divide a stream into two equal parts, the rectangular weir, either with or without end contractions, is entirely satisfactory. In localities where water is distributed to the several parts of the farm in underground pipes it is essential to provide special boxes for making a proportional division of the water. A typical concrete

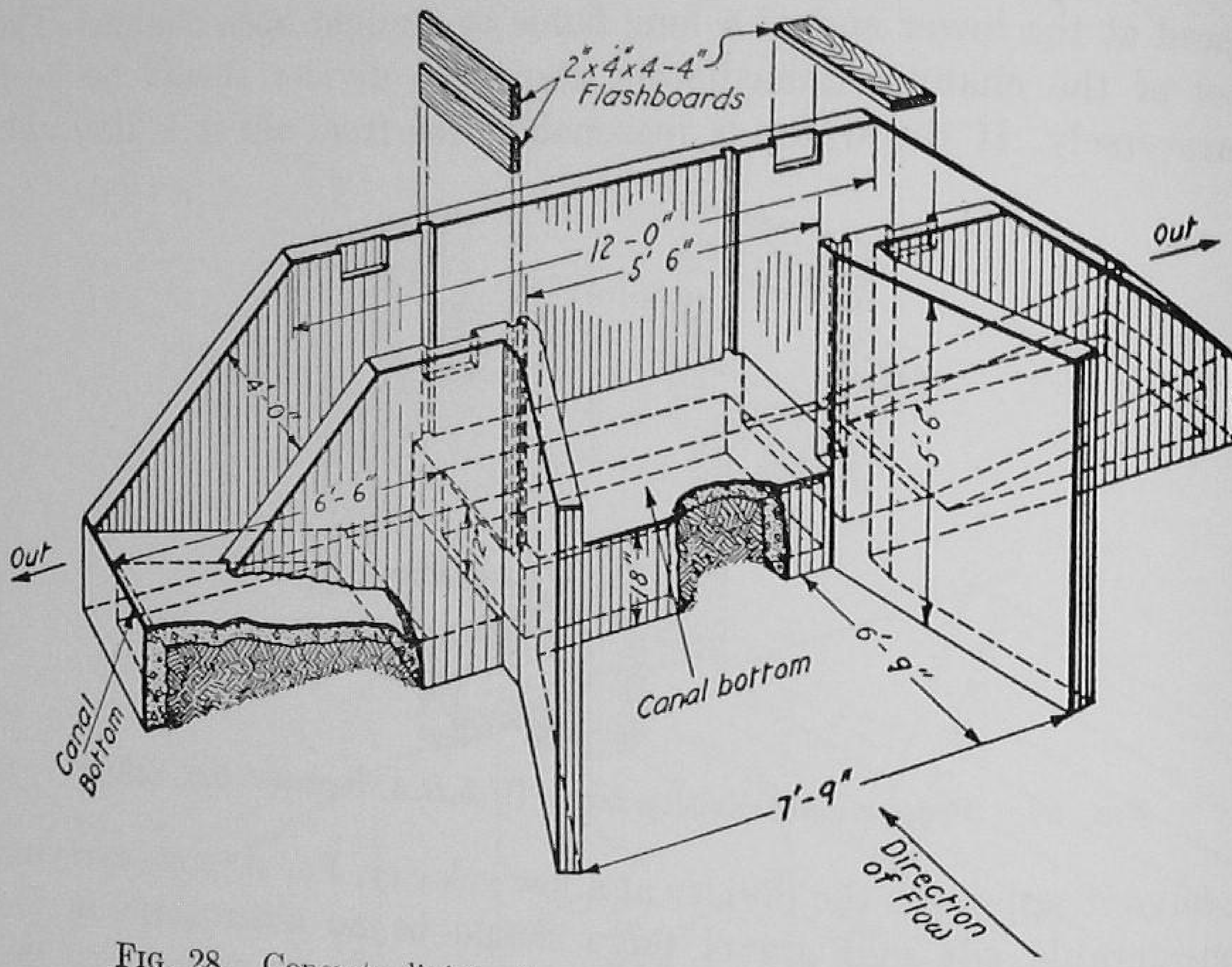


Fig. 28. Concrete division box. (*U.S.D.A. Farmers' Bul.* 1243.)

proportional division box connected to a pipe line is illustrated in Fig. 27, and a concrete division box with flashboards is shown in Fig. 28.

34. Convenient Equivalents The following convenient equivalents are helpful in stream discharge measurements:

UNITS OF FLOW

1. 1 cfs = 50 Utah miner's inches.
2. 1 cfs = 7.48 U. S. gal per sec; 448.8 (approximately 450) gal per min; and 646,272 gal per 24-hr day.
3. 1 cfs = 1 acre-inch per hr (approximately).

UNITS AT REST

4. 1 acre-foot = 325,850 gal = 43,560 cu ft.
5. 1 cu ft of water weighs 62.5 lb.
6. 1 gal of water = 8.36 lb.
7. 1 gal = 231 cu in. (liquid measure).

4

Conveyance of Irrigation Water

Irrigated lands are usually situated great distances from the sources of water supply. Water obtained from natural streams and from surface reservoirs, as a rule, must be conveyed farther than water obtained from underground reservoirs. The main conveyance or diversion canals of American irrigation projects vary from a few miles to 100 or more miles in length. Some projects convey water several hundred miles from storage reservoirs in the mountains by commingling the stored water with the water of natural rivers and then again diverting it into large canal systems in the valleys. Many hours, and on some projects, days, are required to convey the water from points of storage or diversion to points of use. The principles of water flow and the problems of water conveyance, canal seepage losses, canal lining, and maintenance are topics to which entire volumes of technical engineering books are devoted. Some of the forces that cause water flow, and also some of those that retard its flow, are briefly considered in this chapter. The discussion includes only steady flow, i.e., flow in which the same volume of water passes any given point in a channel during a unit of time. With a few minor exceptions, it is assumed also that there is little or no change in velocity from point to point along a channel; that is, the flow is uniform. Seepage-loss measurements, canal lining, and cleaning and maintenance of canals are briefly considered and illustrated.

35. Forces Which Cause Water Flow Water flows in rivers, canals, and in soils as a result of being acted on by forces, the most important of which are:

1. The attraction of the earth, commonly spoken of as the earthpull, or gravity; and
2. The action of pressures of different intensities which give rise to resultant forces.

36. Gravity and Flow in Canals Water flowing in a canal of uniform cross-section area and constant depth has a constant velocity. Every pound of water in a canal is attracted toward the center of the earth by a force which is continuously pulling vertically downward. The resultant force which causes flow is the component of gravity parallel to the water surface. This force is represented by the line F_g in Fig. 29. The slope is defined as the fall in water surface per given length of canal, such as 1 ft per 1000 ft. In Fig. 29 it is represented by h_c/l, as

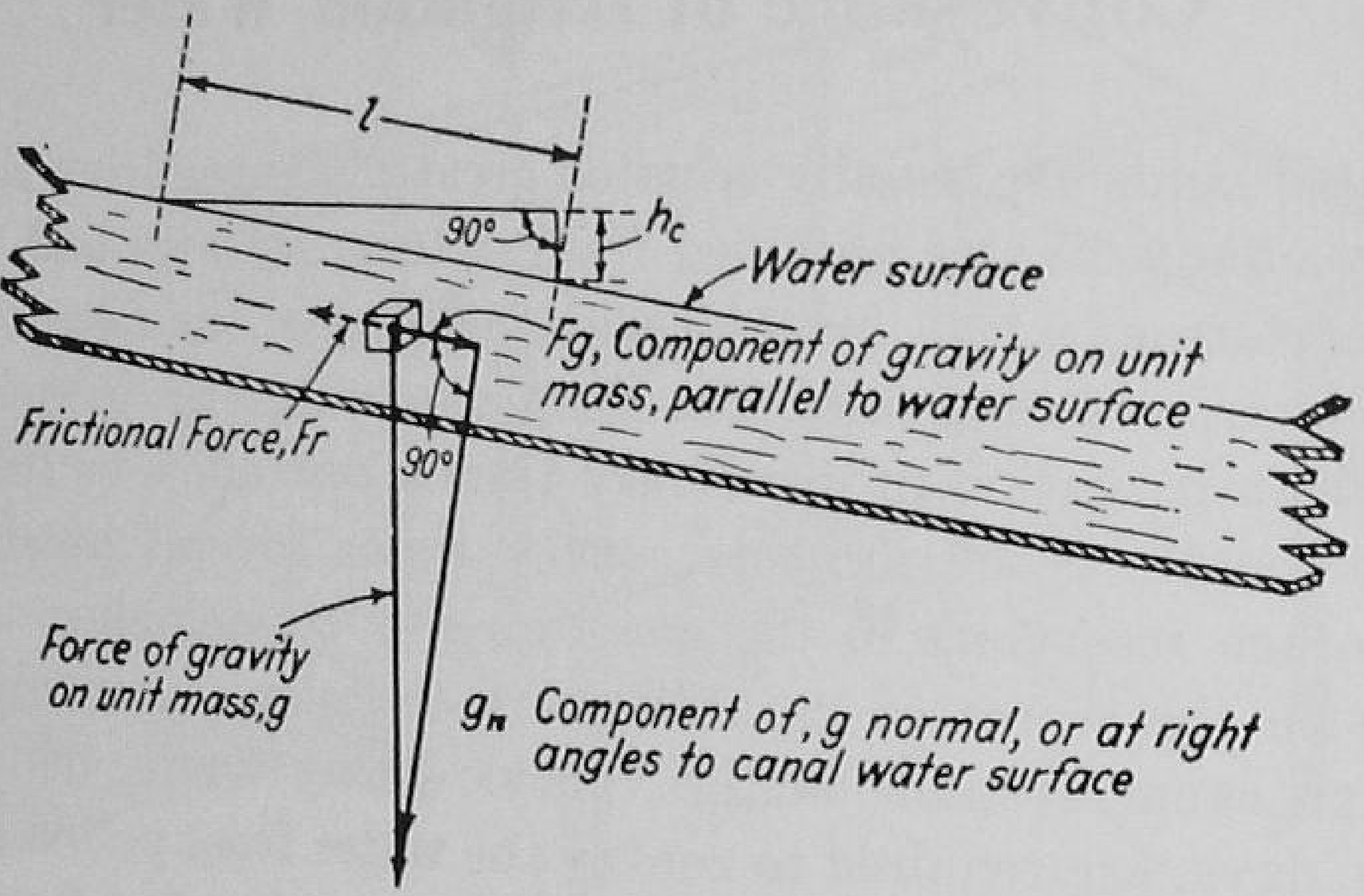


FIG. 29. Illustrating the weight per unit mass and its component parallel to the water surface as the driving force which causes water flow in a canal.

illustrated by the small triangle. The two right triangles are similar, having two sides perpendicular. Therefore

$$\frac{F_g}{h_c} = \frac{g}{l} \qquad \text{and hence} \qquad F_g = \frac{gh_c}{l} \tag{13}$$

Equation 13 and Fig. 29 show that the driving force in each unit weight of water in the direction of flow increases as the slope of the water surface increases. If the slope is zero, i.e., if the water surface is level, h_c = zero, F_g = zero, and there is no flow.

37. Pressure Differences and Flow in a Level Pipe The intensity of water pressure at any point in a body of still water is proportional to the depth of the point below the water surface. This relation, widely used in engineering, is stated mathematically as

$$p = wH \tag{14}$$

where p = intensity of pressure (lb per sq ft);
w = weight of unit volume of water (lb per cu ft);
H = depth of the point vertically below the water surface (ft).

The pressure difference at two points designated as points 1 and 2 may be obtained thus:

$$p_2 = wH_2 \qquad (a)$$

$$p_1 = wH_1 \qquad (b)$$

Subtracting equation (b) from (a),

$$p_2 - p_1 = w(H_2 - H_1) \qquad (c)$$

For convenience, the pressure difference at any two points, $(p_2 - p_1)$, is represented by p' and the difference in depth $(H_2 - H_1)$ is represented by h_0. It then follows that

$$p' = wh_0 \quad \text{and} \quad h_0 = \frac{p'}{w} \qquad (15)$$

The force on each unit weight causing flow through a level pipe is *proportional* to the pressure-head difference h_0 or p'/w per unit length of pipe.

Measurements of the pressure-head differences are illustrated in Fig. 30 which shows a level pipe, A–B, connected to a reservoir, R, into which a stream of water is flowing. The inflow is just large enough to maintain the water level constant at a distance H' feet above the middle of the outlet pipe. The six small vertical pipes, called piezometers, numbered 1, 2, 3, etc., are connected with the large pipe in order to measure the pressure heads at various points along the large horizontal pipe. When the valve near the outlet end of the large pipe is closed, the water stands at the elevation E' in pipe 6, the same elevation as it is in the reservoir, and in each of the other piezometer tubes. The total pressure on unit area inside the large pipe at B is equal to the atmospheric pressure on unit area plus the water pressure due to the column of water of height H', when the valve is closed; but as soon as it is opened, water flows out because the total pressure inside the pipe is higher than the atmospheric pressure outside. After the flow through the large pipe has reached a steady state, the water in each of the several piezometer tubes will stand as indicated by the dotted line E–B, neglecting the loss at the entrance. The difference in the pressure heads as measured in piezometers 1 and 2 is given by the equation

$$h_2 = \frac{p_1 - p_2}{w} \qquad (d)$$

Remembering that the h_0 represents a pressure-head difference in a given length of level pipe, l, it can be seen that the resultant driving

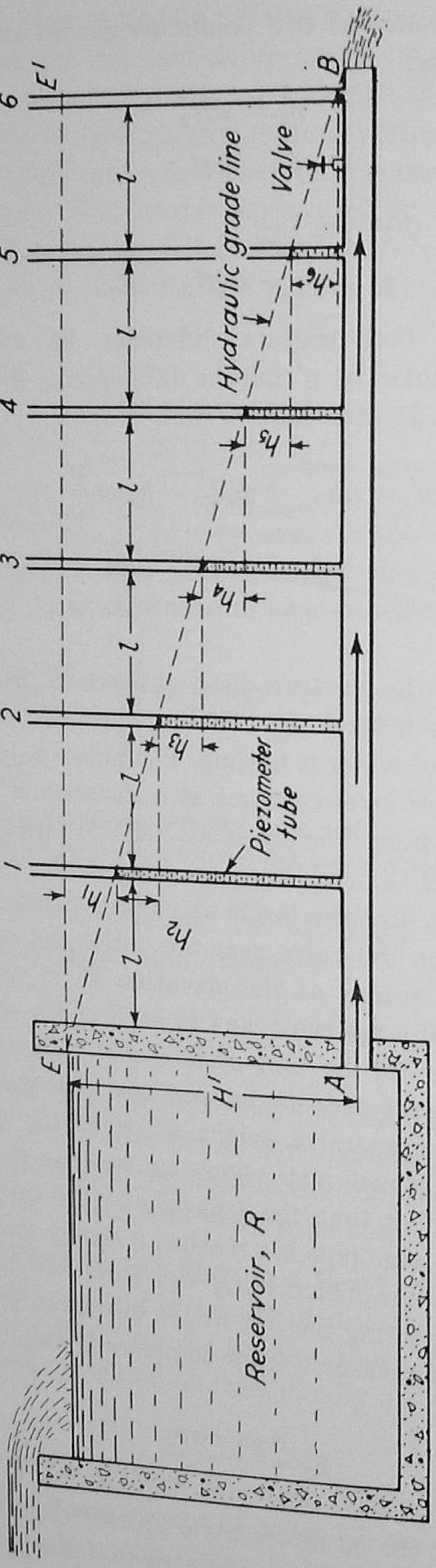


Fig. 30. Illustrating the position of the hydraulic grade line as water flows through a horizontal pipe line from a reservoir in which the water is maintained at constant depth.

force, F_p, on each unit weight of water, is due to pressure-head differences, which is given by the equation

$$F_p = \frac{h_0}{l} \tag{16}$$

38. Flow in an Inclined Pipe Provided that the velocity of flow is constant in a sloping pipe, the total driving force per unit weight of water, F, is equal to the sum of the forces $F_g + F_p$ of equations 13 and 16, i.e.,

$$F = \frac{h_c + h_0}{l} \tag{17}$$

This is illustrated in Fig. 31. At the point 1 the combined *energy* head per unit weight due to position with respect to the plane M, and to pressure, is represented by the sum $h_e' + h_p'$. The resultant driving force on unit weight due to the combined effect of differences in position and in pressure between the points 1 and 2 separated by a distance l is given by:

$$F = [(h_e' + h_p') - (h_e'' + h_p'')] = \frac{h_f}{l} \tag{18}$$

where h_f = the drop in the hydraulic grade line* in the distance l as shown in Fig. 31.

Comparison of equations 13 and 18 shows that the slope of the line connecting the heights to which water will rise above a pipe line because of the water pressures inside the pipe is somewhat analogous to the slope of the water surface in open channels. The foregoing analysis shows that the driving force per unit weight causing water flow may be a component of gravity, equation 13, a pressure-head gradient, or a combination of these two, equation 18.

39. Retarding Forces Motion of all substances, including water, is retarded by the resistance of one body moving over another with which it is in contact. For example, a moving train is retarded by its contact with the rails. Forces of this type which resist motion are called *frictional forces*. In a canal, the necessary condition for a constant velocity of water is that the frictional force per unit weight resisting motion, i.e., F_r in Fig. 29, is equal in magnitude to the driving force, F_g. If, at a given length of the canal, the slope increases, the driving force, F_g, is also increased and the water will be accelerated and its velocity increased. The increase in velocity increases the frictional

* See Article 40 and Fig. 33 for the meaning of the term "hydraulic grade line."

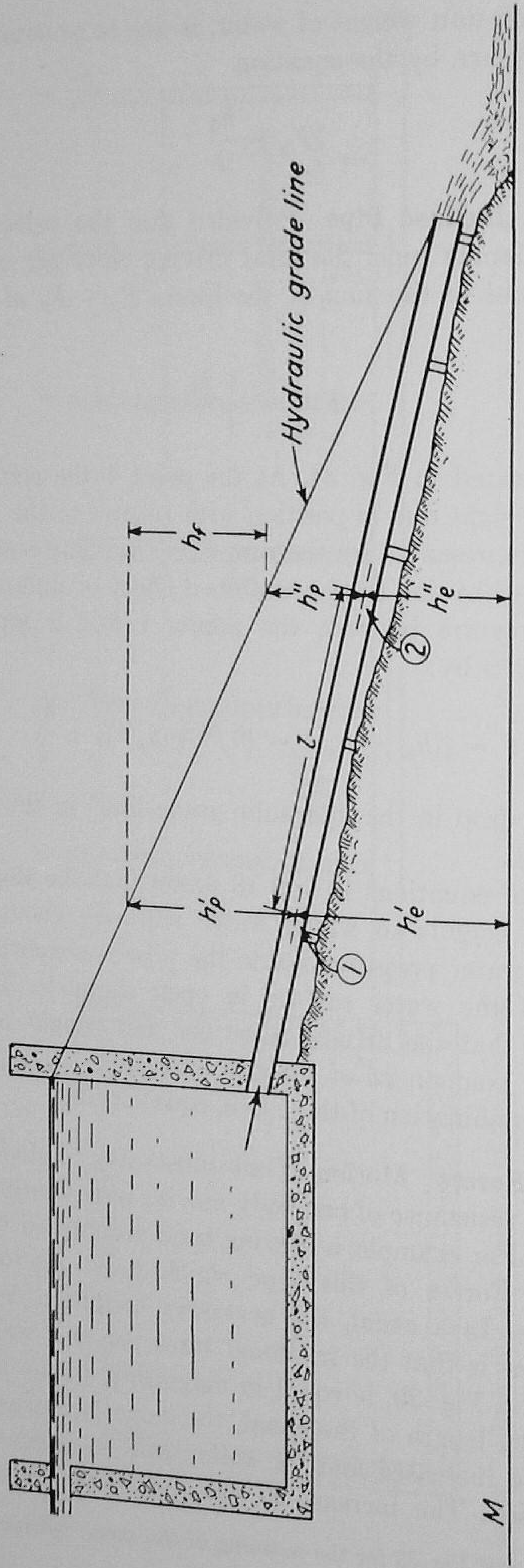


FIG. 31. Illustrating the flow of water through a sloping pipe.

resistance until F_r again equals F_g (in magnitude).* As a result of experiments on the relation of friction to velocity of water in canals and pipes, it is agreed that, when the velocity exceeds the *critical velocity* and the flow is turbulent, the frictional resistance varies approximately with the square of the velocity.

Remembering that h_c/l is the slope of the water surface in a canal and that h_f/l is the hydraulic slope (Fig. 31), it follows that for flow of water in a particular canal or a pipe the velocity equals a constant times the square root of the slope, i.e.,

$$V = C \times \sqrt{\text{Slope}} \qquad (19)$$

The frictional forces which retard the velocity of water in a canal are influenced by the relative area of the surface of contact between the water and the bottom and sides of the channel per unit of length and also by the degree of roughness of the material of which the channel is built. The relative area of surface contact between water and channel, as represented by the ratio of the cross-sectional area of the canal to the wetted perimeter, is termed the hydraulic radius and is represented by the symbol r. For example, a rectangular canal having a bed width of 5 ft and depth of 2 ft has a cross-sectional area of 10 sq ft and a wetted perimeter of 9 ft, from which the hydraulic radius is $^{10}\!/\!_9$ ft. The hydraulic radius of a circular pipe running full of water is one-fourth of the diameter.

40. Energy and Hydraulic Grade Lines Expenditures of energy are essential to make water flow. Mechanical work is defined as the product of force by distance, and mechanical energy is the capacity for doing work. Each unit weight of water in a flowing stream has three forms of energy: one of position, one of pressure, and one of velocity. The loss in total energy per unit weight of water for each unit length of canal is represented by the lines marked energy grade line in Fig. 32 and Fig. 33. The loss of energy per unit of weight of water per foot length of a canal of uniform cross section and depth of water is constant as shown by the energy grade line of Fig. 32. For flow in pipes, the slope of the energy grade line changes at points where the diameter of the pipe changes; but the energy grade line always falls, as shown in Fig. 33, whereas the hydraulic grade line rises at sections

* In the flow of water in canals and pipes there are eddies and cross currents. The water particles move in rather irregular zigzag directions; such flow is spoken of as a *turbulent flow*, as contrasted to *streamline flow*, which is characteristic of the slow flow of water through sands, or very small tubes. There are no eddies or cross currents in streamline flow.

where the velocity head is suddenly decreased and the pressure head increased.

In general, the driving force per unit weight of water is *proportional* to some function of the slope of the energy grade line, i.e., to the loss of energy per unit length of pipe or canal. In any given pipe line of uniform diameter in which water flows at a constant velocity, the

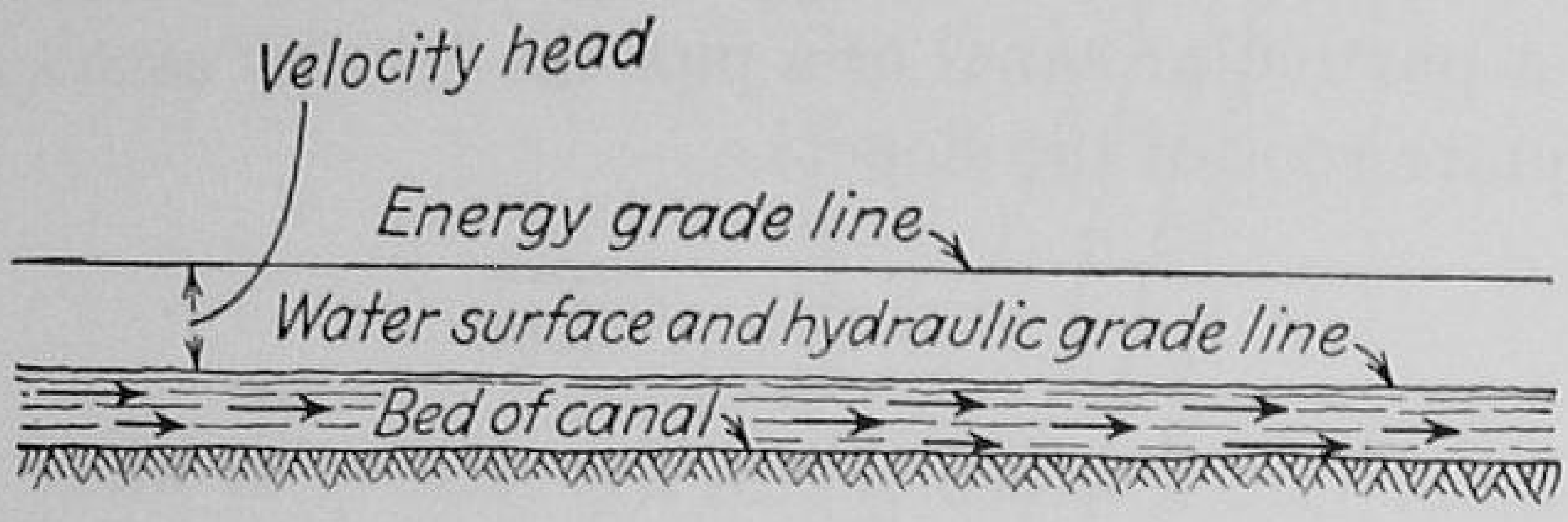


FIG. 32. Open canal showing water surface (hydraulic grade line) and energy grade line.

velocity is proportional approximately to the square root of the slope of the hydraulic grade line, as shown in equation 19.

It is important to note that in computing the slope of the hydraulic or energy grade lines the length l is measured along the canal or the pipe, not along the line. The length along the canal or pipe is the same as the length of the line between two points only in steady

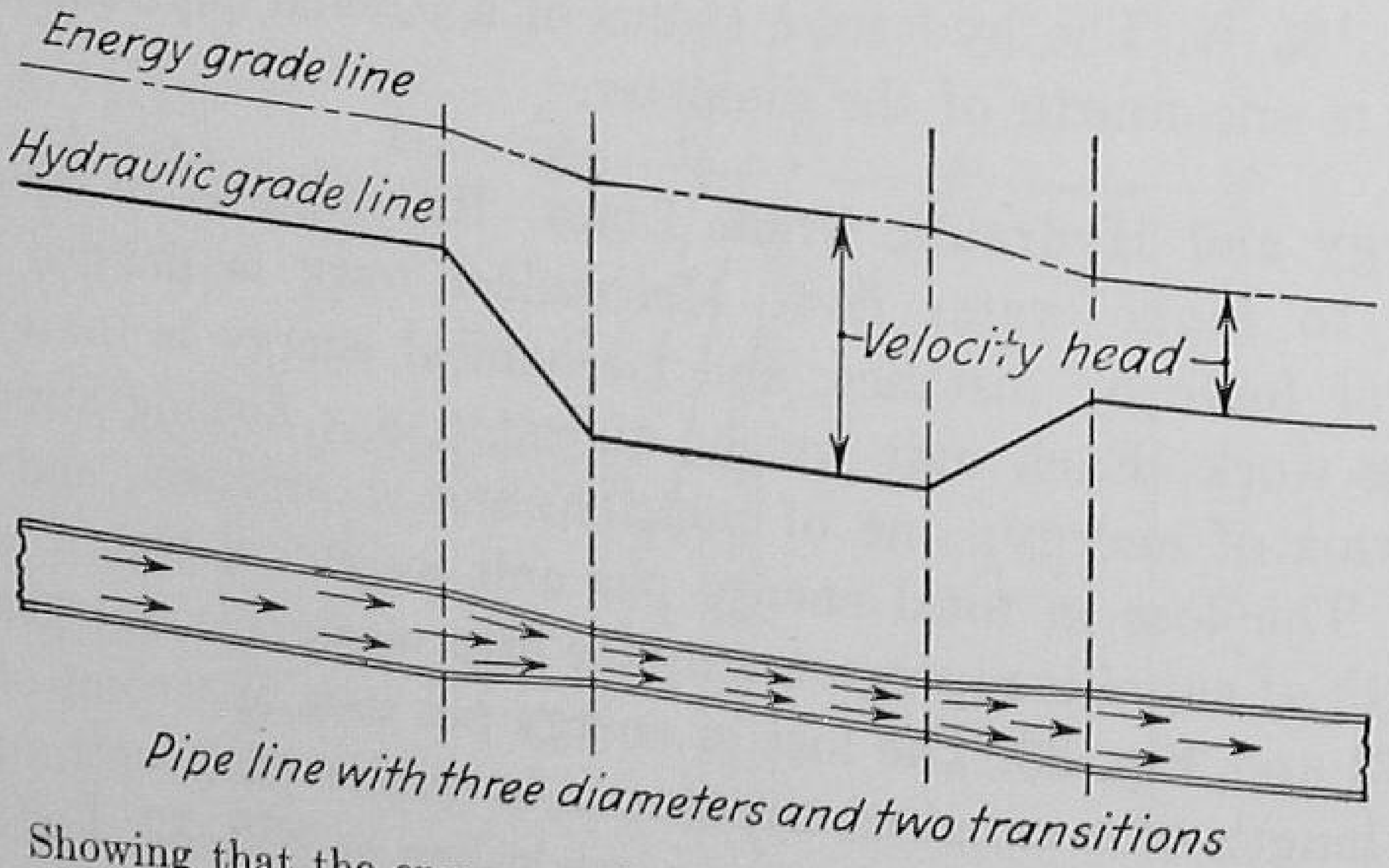


FIG. 33. Showing that the energy grade line always falls in the direction of flow.

uniform flow in a canal or in a pipe in which the hydraulic or energy grade line is parallel to the pipe line. (See Figs. 29 to 33.)

Energy and hydraulic grade lines are considered further in Chapter 10 in connection with the study of the flow of water in soils.

41. Velocity Equations Experiments have been conducted in order to ascertain the numerical relation between the velocity of flowing water,

the degree of roughness, the hydraulic radius, and the slope of the channel, and thus to obtain a velocity equation of general value. These experiments have resulted in a number of closely related velocity equations, most of which have much merit. Of these equations, the one proposed by Chézy using the Kutter formula to evaluate C, the Manning equation, and the equations derived by Scobey are widely used. The Manning equation follows:*

$$v = \frac{1.486 r^{2/3} s^{1/2}}{n} \tag{20}$$

in which v = mean velocity in feet per second;
n = coefficient of roughness, which is also used in the Kutter formula;
r = hydraulic radius in feet;
s = slope of the canal water surface or the hydraulic slope.

By the use of Table 11 the student can select n, and he can then determine v when r and s are known. (The selection of n from Table 11 is very important, as the velocity varies inversely with its values.) By the use of equation 3 (Chapter 3), $q = av$, we are able to determine the quantity of flow in a canal, after finding the velocity.

42. Earth Canals The most common type of irrigation conveyance channel is the one excavated in the natural material along the line that the water must be conveyed. When used without artificial lining of bed or sides, such a channel is called an earth canal. Excessive velocities of water in earth canals cause erosion. Very few natural materials will stand velocities in excess of 5 ft per sec. The low initial cost constitutes the major advantage of earth canals. The disadvantages are: (*a*) excessive seepage losses, (b) low velocities and therefore relatively large cross-section areas, (*c*) danger of breaks due to erosion and the burrowing of animals, and (*d*) favorable conditions for growth of moss and weeds which retard the velocity and cause high annual maintenance costs (Fig. 34). The sides of earth canals are usually built as steep as the earth will stand when wet. The slope of the sides varies from 3 horizontal and 1 vertical to 1 horizontal and 1 vertical, for very stable materials. The relation of bed width, b, to depth of earth canals, d, is determined according to the topographic conditions. The bed width may be less than the depth, or it may be 10 or more times the depth. The most economical cross section under

* Manning's equation is presented because of its simplicity despite the fact that other velocity equations are widely used in the design of irrigation conduits.

favorable structural conditions is

$$b = 2d \tan \frac{\theta}{2} \tag{21}$$

where θ is the angle of the side slope with the horizontal. This relation applies also to lined canals. For rectangular channels $\tan \theta/2 = 1$, and hence the bed width equals twice the depth.

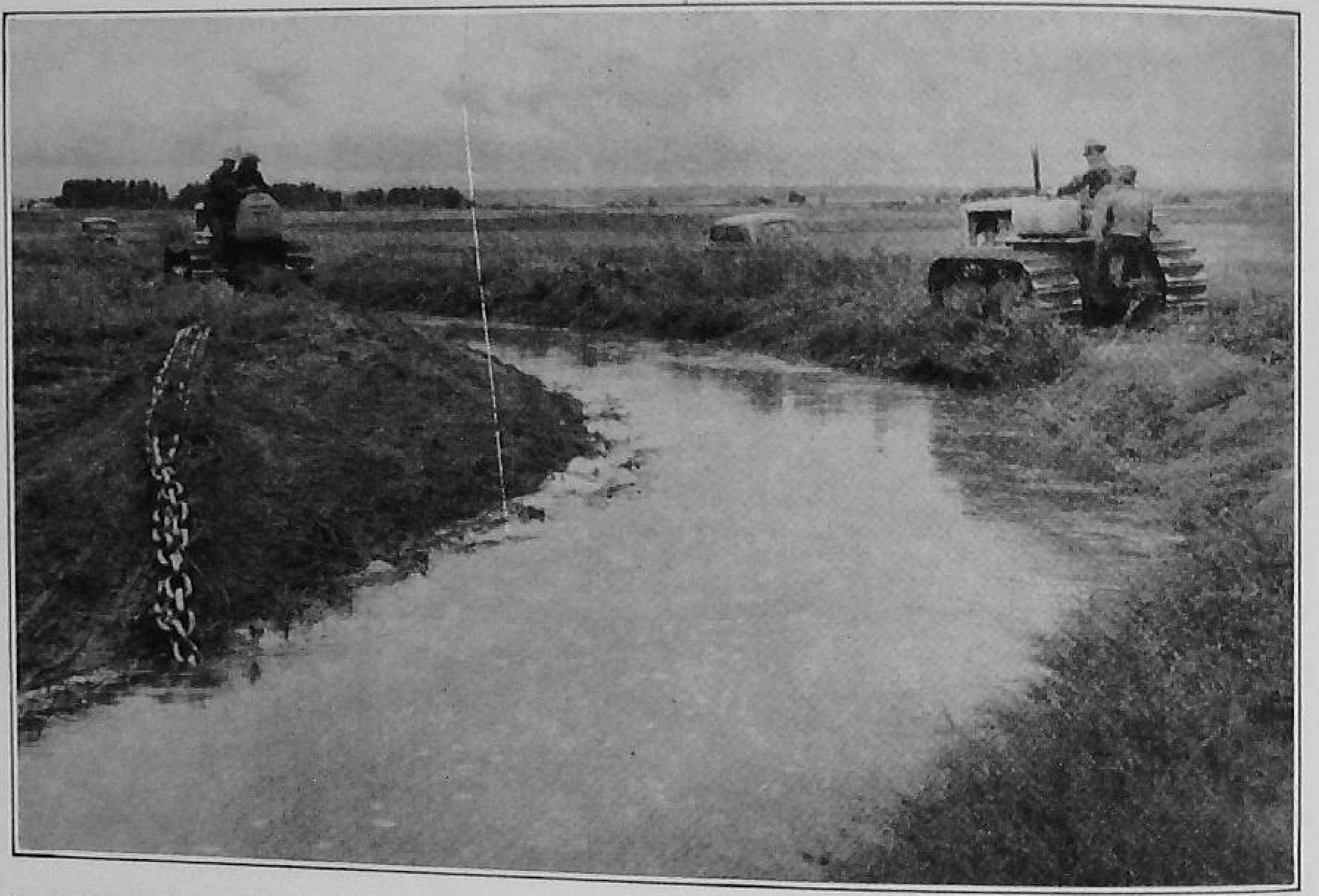


FIG. 34. Diesel tractors owned by North Side Canal Company, Jerome, Idaho, pulling a large chain weighing 2300 lb to loosen moss and weeds in bottom of a canal. (Courtesy Caterpillar Tractor Company.)

43. Water Conveyance and Delivery Efficiency It is impracticable, as a rule, to convey irrigation water from its source in rivers to the irrigated farms without sustaining certain losses through leaky irrigation gates, spillways, wasteways, evaporation, and seepage. Let

E_c = the water conveyance and delivery efficiency, percent.
W_r = the water diverted from the river or reservoir into the irrigation canal.
W_f = the water delivered to the farms under the canal. (See Table QR, page 23, item 38.)

Then, by definition,

$$E_c = \frac{100W_f}{W_r} \tag{22}$$

The water conveyance and delivery efficiency, E_c, is thus defined as the ratio of the sum of the water delivered to all the farms to the water diverted from the river or other water source during the same time period.

The 17 western states, in 1940, had 125,000 miles of irrigation canals and laterals. It is estimated that, of the 90 million acre-feet of water diverted for irrigation in 1939, 38 percent was lost between the points of diversion and delivery, thus making $E_c = 62$ percent.

This low average water-conveyance efficiency is caused largely by heavy seepage losses from unlined canals in highly permeable earth materials. In 1939 only 5000 miles of canals had been lined, merely 4 percent of the 125,000 miles of irrigation canals.

The conveyance and delivery losses of one canal system in some valleys seep back to the river and are later diverted by other canals lower on the river system, so that the low values of E_c are in reality less serious than they sometimes appear to be. Despite these recoveries of waste water for lower lands in some localities, it is important, as a general rule, that conveyance and delivery losses be reduced to a reasonable minimum, thereby increasing E_c.

Seepage from canals is influenced by many variable factors and is therefore difficult to measure accurately. In large main canals, losses within selected substantial canal length sections having few or no diversions are determined by subtracting the outflow at the lower end of the section from the inflow at the upper end. For measuring inflow and outflow, current meters are common, but weirs and measuring flumes also are used. In short sections of canals, the seepage losses may be significant and serious but yet too small to measure by the inflow-outflow method.

Seepage losses from canal sections may be approximated, but not accurately determined, by measuring the permeability of the canal bed and bank materials, the wetted area, and the hydraulic slopes causing the seepage and ground-water flow. Chapter 10 presents details concerning soil-permeability measurements. The most certain method of obtaining reliable seepage-loss measurements is to build a pool in a long section of the canal to be tested and thus measure the seepage through relatively large areas of canal beds and banks.

Of equal importance to measuring the seepage loss in a canal is the realization that seepage losses are taking place. On many of the older main canals and on the farm laterals, the owners have become so accustomed to the losses that they do not realize either the extent or the seriousness of them. Occasionally, inspection of lands near canals

and of the downstream side of a canal show the effects of heavy seepage.

44. Lining Canals For the purposes of (1) decreasing conveyance-seepage losses, (2) providing safety against breaks, (3) preventing weed growth, (4) retarding moss growth, (5) decreasing erosion with high velocities, (6) cutting down maintenance costs, and (7) increasing the capacity of the canal to convey water, some irrigation canals are lined. A few canals have been lined under low-cost methods with

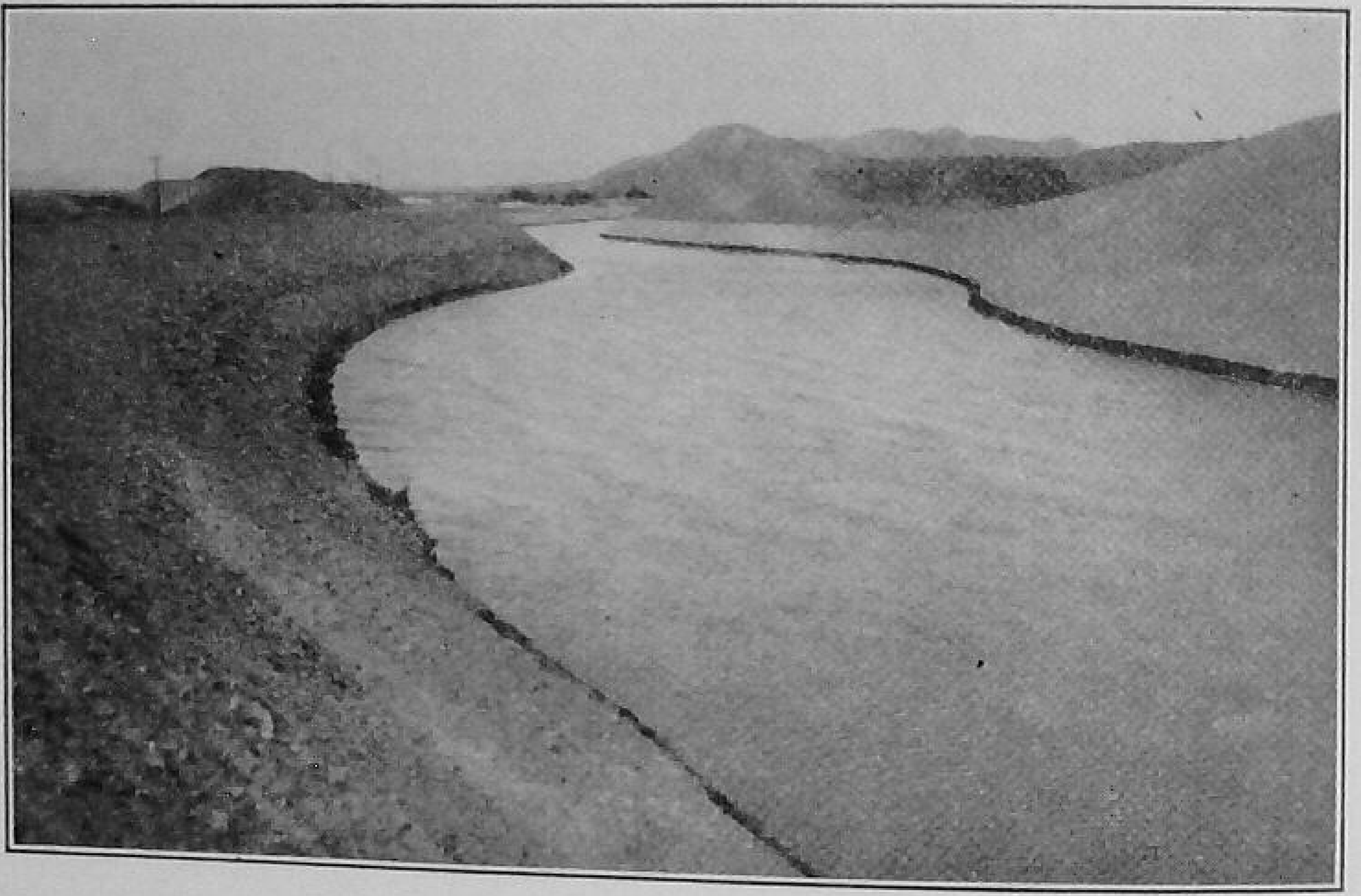


FIG. 35. All-American Canal clay blanket lining looking downstream. The white sand in which the canal is built has a permeability 1800 times higher than the clay used for lining. (Photograph by author, October 1940.)

clay, as illustrated by Fig. 35, and with asphalt membrane. Detailed cost studies are essential to a determination of the economic advisability of lined canals. From the viewpoint of the irrigation project, the most important single factor in a study of the advisability of lining is the annual value of the water saved by decreasing conveyance losses. In localities where water is very limited, the public interests are advanced by lining canals and thus contributing to a more economical use of the available water supply.

Excess canal seepage contributes to waterlogging of farm lands, alkali concentration in the soils, costly road maintenance and drainage activities, ground-water seepage into basements of buildings, and other conditions that concern the public. Although it is difficult, costly, and sometimes quite impractical to measure accurately the degree of contribution to these adverse conditions by any one canal, the public should encourage reduction of canal seepage to protect public interests.

FIG. 36. The concrete-lined Kittitas Main Canal, looking downstream, Yakima Project in the State of Washington, carrying about 600 cfs of water. (*Reclamation Era*, August 1946.)

FIG. 37. Placing 8-in. by 24-in. precast concrete slabs with tongue and groove joints. Yakima Project, Washington, 1947. (Courtesy Bureau of Reclamation.)

45. Materials for Canal Lining The most-used materials for canal lining include concrete, rock masonry, brick, bentonite-earth mixtures, natural clays of low permeability, and different rubber compounds. For the main canal of the Yakima Project in the state of Washington, shown in Fig. 36, concrete prevents both seepage and erosion.

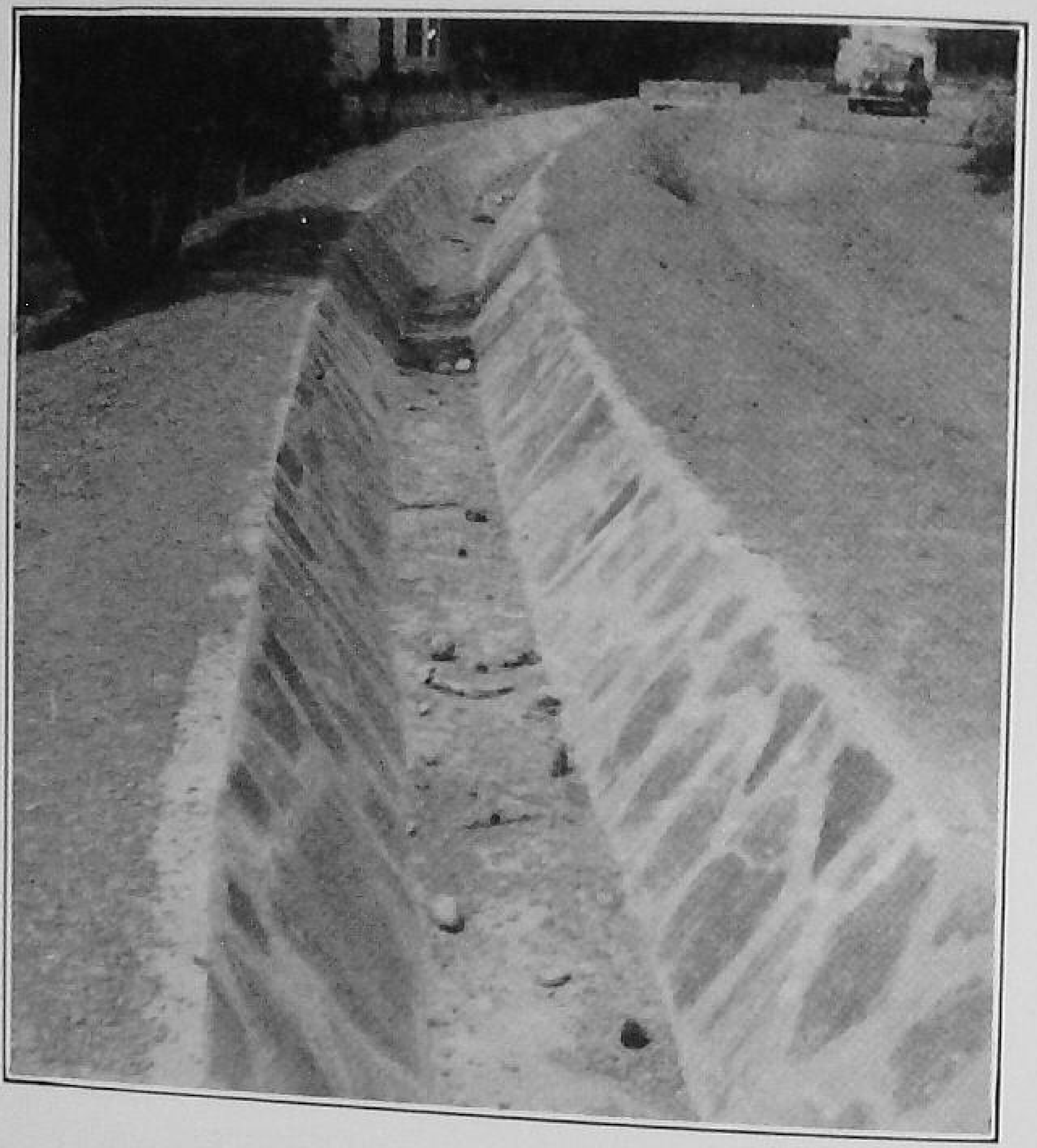


FIG. 38. A serviceable and attractive small Utah canal lined to solve the seepage, erosion, and weed problems. (Courtesy Work Projects Administration.)

For the smaller irrigation canals and laterals precast concrete slabs made at regular concrete mixing plants and hauled to and placed in canals, as illustrated in Fig. 37, are helpful. Both frequent inspection of the concrete slab joints and careful maintenance are essential to prevent erosion of soil materials under the slabs and resulting settlement and damage to the lining.

46. Construction Methods for Canal Lining In the earlier days of canal lining, much of the work, of necessity, was done by hand labor. A rock masonry canal lining constructed near Salt Lake City when labor was abundant is shown in Fig. 38. There has been substantial progress in the application of mechanical methods and mechanical power to the lining of irrigation canals. The use of a modern mechanical concrete laying machine for lining small canals is shown in Fig. 39.

An outstanding example of the use of modern machinery in lining large irrigation canals is shown in Fig. 40, which illustrates the Trimmer and Slip-Form speed lining operations on Friant-Kern Canal in California's Central Valley Project.

FIG. 39. Concrete-laying machine makes it possible to lay 800 ft of concrete lining per day. Invented by the Vawdrey Brothers of Draper, Utah. (Photograph by J. R. Barker.)

47. Keeping Canals Clean One of the vital maintenance problems in conveyance of irrigation water is cleaning canals. Growth of weeds and willows on canal banks and of mosses and other aquatic plants in the canals greatly retards water velocities and decreases capacities of canals. Silt and clay deposits in canal beds also restrict water flow. Hand-labor methods of canal cleaning are being replaced by the use of bulldozers, drag-line excavators, and tractor-drawn chains as shown in Fig. 34. For loosening water weeds and silt in concrete-lined canals, a water-propelled scraper may be used as shown in Fig. 41. Dense weed growth prevents proper inspection of the canal bank; as a result gopher holes and other defects that may cause ditch breaks are hard to find.

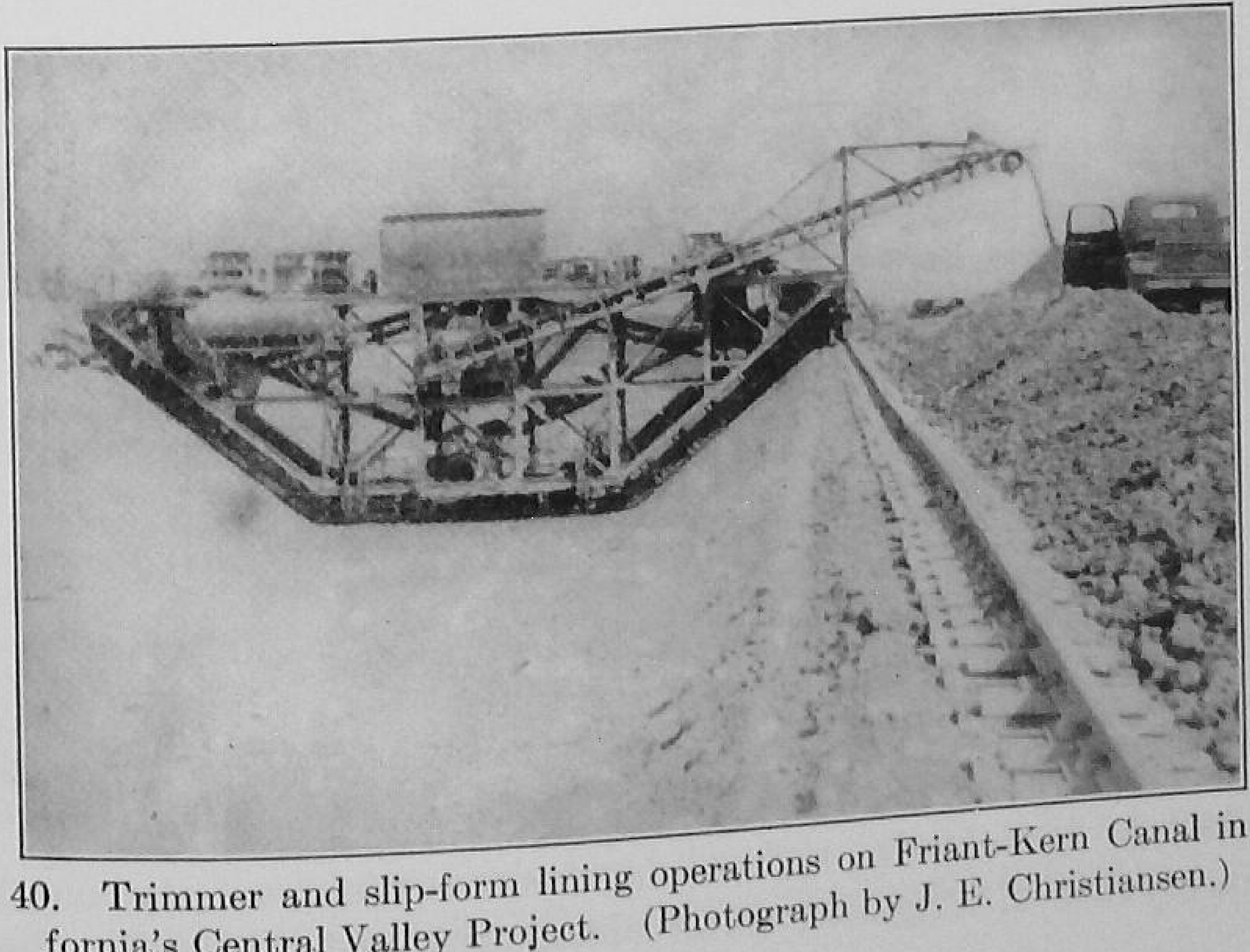


FIG. 40. Trimmer and slip-form lining operations on Friant-Kern Canal in California's Central Valley Project. (Photograph by J. E. Christiansen.)

Weeds fall into the water and catch floating debris, retard flow, and cause failure of the banks. The larger perennials such as willows, tamarisk, and cane make it almost impossible to clean a canal and remove the smaller weeds. In addition to the operational problem many of the land weeds developing seed along a canal bank are a source of weed infestation to crop land.

FIG. 41. A water-propelled scraper can be used to cut loose water weeds and silt from the bottom and sides of concrete-lined channels. (From *Control of Weeds on Irrigation Systems*, Bureau of Reclamation, July 1946.)

Water weeds such as tules, cattails, pondweeds, coontail, and chara also reduce the capacity of flow. These weeds, like those on the banks, often clog measuring flumes, weirs, spillways, and other parts of the irrigation system, causing delays and additional costs in cleaning. Weed growths cause sand and silt bars to build up in the channel, which retard the velocity of flow and increase the seepage loss and at times cause overflows of the bank. This results in delays and damage to the canal and the crops.

The most common methods of controlling weeds on the canal banks are: pasturing, mowing, burning, and the application of chemical weed killers. The methods for controlling the water-weed growths may be classed under four main heads, mechanical, drying, shading, and chemical. Hand-labor methods of canal cleaning are being replaced by less costly methods.

48. Flumes For crossing natural depressions or narrow canyons, and for conveyance of irrigation water along very steep side hills, flumes

FIG. 42. Small flume crossing over arroyo in Upper Anton Chico. This structure saved 1700 ft of ditch length. Guadalupe County, New Mexico. (Courtesy Soil Conservation Service.)

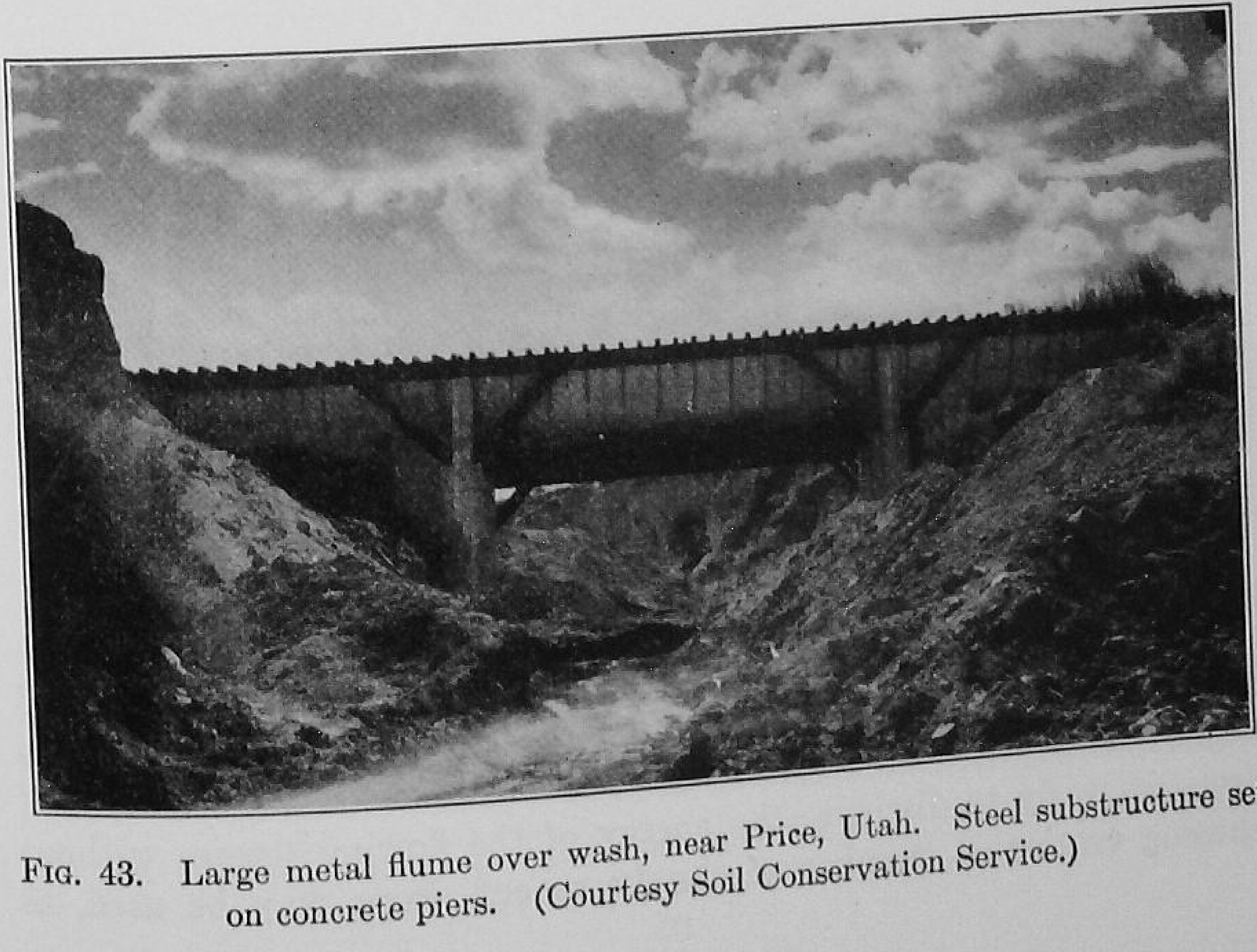


FIG. 43. Large metal flume over wash, near Price, Utah. Steel substructure set on concrete piers. (Courtesy Soil Conservation Service.)

are constructed either of wood or metal, or both, as shown in Fig. 42 and Fig. 43. Concrete is also used for flumes. To attain economy in the application of materials for flumes, it is desirable to give the flume sufficient slope to assure a water velocity appreciably higher than in earth canals, thus making possible a proportionate reduction in flume cross section.

FIG. 44. A masonry canal drop. Long apron reduces erosion below the structure. Suitable for small canals and low drops. (Courtesy Soil Conservation Service.)

49. Tunnels To shorten the length of the diversion canal, to avoid difficult and expensive construction on steep, rocky hillsides, and to convey irrigation water through mountains from one watershed to another, many tunnels have been constructed. It is usually economical to line the bottom and sides of tunnels through rock formations as a means of decreasing seepage losses and lessening the frictional resistance. Irrigation tunnels constructed through loose material are lined with concrete as the boring of the tunnel progresses.

50. Drops and Chutes In places where the natural slopes down which canals must flow are so high as to cause excessive water velocities and erosion, wood, concrete, or masonry bulkheads are placed, as shown in Fig. 44, over which the water is dropped several feet. The function of drops is really to dissipate the energy of the flowing stream without causing erosion. A number of closely spaced drops may be used, as

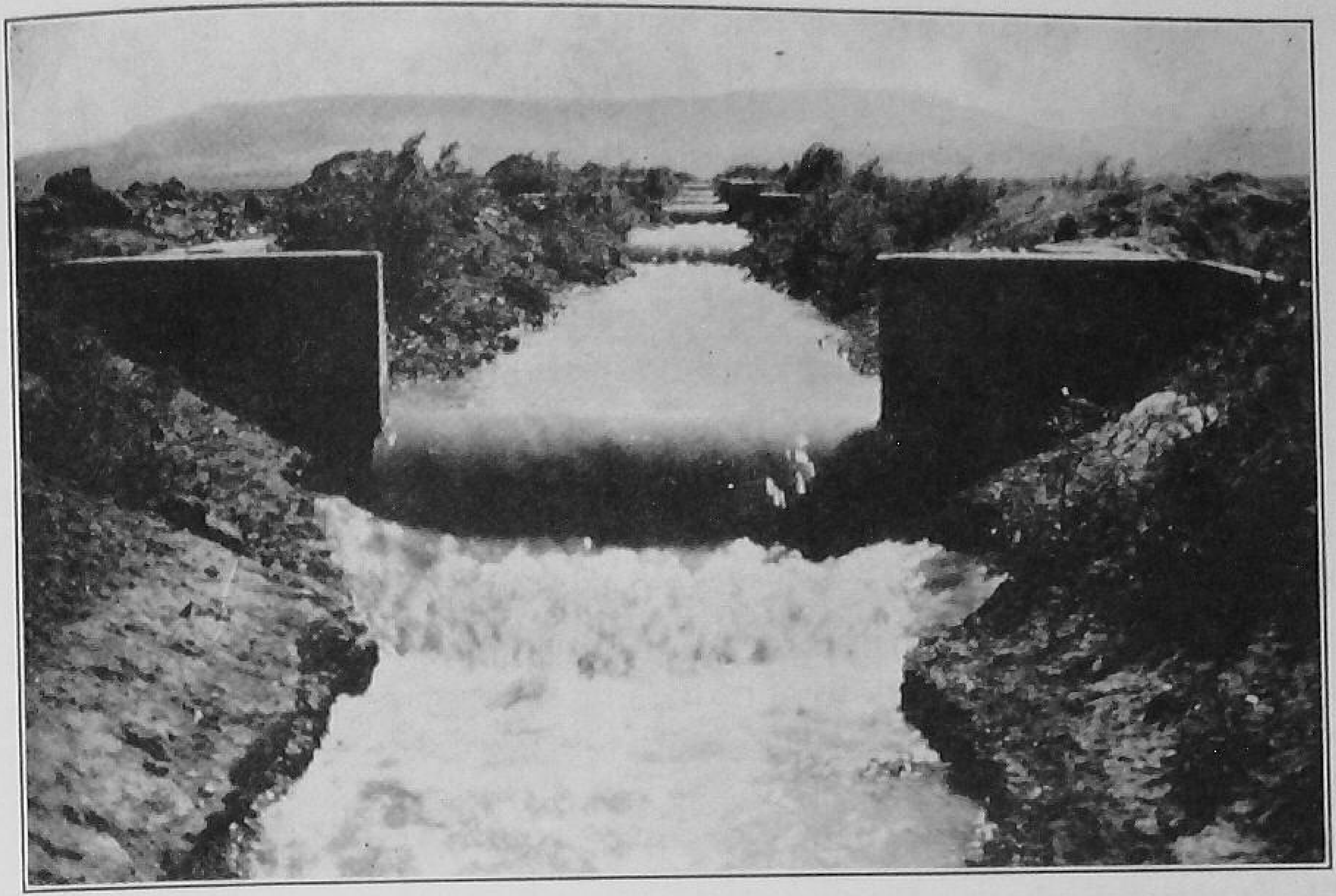


FIG. 45. Series of check drops to prevent high canal water velocities and erosion. Flashboards can be placed in notch to raise water level so that farmer can irrigate fields on both sides of the canal. (Structure in foreground appears to have apron set too high.) (Courtesy Soil Conservation Service.)

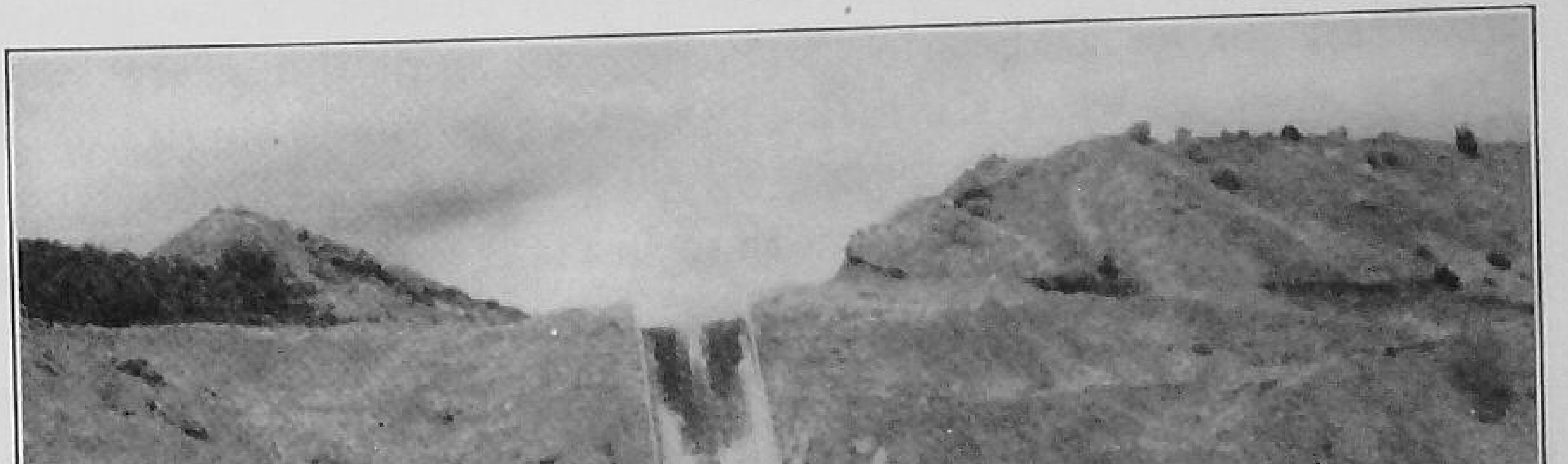


FIG. 46. Concrete chute conveying a stream of 282 sec-ft. Weber-Provo diversion canal. (Courtesy Bureau of Reclamation.)

shown in Fig. 45. Chutes built of wood, concrete, or steel, as shown in Fig. 46, are serviceable where it is necessary to convey water down relatively steep hills which would require many drops closely spaced to control the water velocity, and in which the water would cause serious erosion if not controlled. Chutes may well be considered in three sections: (1) the transition and section of accelerating velocity, (2) the section of uniform high velocity, and (3) the stilling basin. In the first section the velocity is increased from approximately 3 ft per sec up to 20 or more ft per sec, and the cross-section area of the water is proportionately decreased. In the second section, because of the very high velocity, the retarding forces are equal in magnitude and opposite in direction to the driving forces and hence the water velocity remains constant. To dissipate the velocity energy at the lower end of a chute, it is necessary to provide a deep stilling basin.

51. Inverted Siphons For crossing wide deep hollows, depressions, or canyons, it is customary to build pipe lines and convey water through them under pressure. The cost of flumes for crossing wide depressions is so high as to prohibit their construction. Pipes by which irrigation water is conveyed across canyons usually built on or near the ground surface are known as inverted siphons. Such pipe lines are built either of steel, of wood staves held in place by iron bands, or of reinforced concrete. A wood-stave inverted siphon across the Bear River in Idaho resists a water-pressure head of nearly 300 ft along the bottom of the canyon.

The stress caused by the water pressure in siphons is resisted by the unit strength and thickness of steel in steel pipes; by the unit strength, diameter, and spacing of the iron bands around wood stave pipe; and by the unit strength and amount of steel reinforcement in concrete pipe. Large-diameter siphons require respectively thicker steel, larger and more closely spaced bands, and more steel reinforcement than small-diameter siphons under the same water pressure. The velocity of the water flowing through a siphon of given diameter is fixed by the hydraulic slope and by the roughness of the inside of the pipe. The velocity is not influenced by the total water pressure inside the pipe. To determine the velocity the student may use Manning's formula given in Article 41, together with Table 11. For example, consider a 6-ft-diameter wood stave siphon in the best of condition, 1 mile long, having a drop in water surface of 9 ft. Then $r = 1.5$ and $s = 0.0017$; from Table 11, $n = 0.01$. Therefore, $v = 8.03$ ft per sec. As the cross-section area of a 6-ft-diameter pipe is 28.3 sq ft, this pipe would discharge $8.03 \times 28.3 = 227$ cfs.

TABLE 11

HORTON'S VALUES OF n. TO BE USED WITH KUTTER'S AND MANNING'S FORMULAS

Surface	Best	Good	Fair	Bad
Uncoated cast-iron pipe	0.012	0.013	0.014	0.015
Coated cast-iron pipe	.011	.012*	.013*	
Commercial wrought-iron pipe, black	.012	.013	.014*	.015
Commercial wrought-iron pipe, galvanized	.013	.014	.015	.017
Smooth brass and glass pipe	.009	.010	.011	.013
Smooth lockbar and welded "OD" pipe	.010	.011*	.013*	
Riveted and spiral steel pipe	.013	.015*	.017*	
Vitrified sewer pipe	{ .010 .011	.013*	.015	.017
Common clay drainage tile	.011	.012*	.014*	.017
Glazed brickwork	.011	.012	.013*	.015
Brick in cement mortar; brick sewers	.012	.013	.015*	.017
Neat cement surfaces	.010	.011	.012	.013
Cement mortar surfaces	.011	.012	.013*	.015
Concrete pipe	.012	.013	.015*	.016
Wood stave pipe	.010	.011	.012	.013
Plank Flumes:				
Planed	.010	.012*	.013	.014
Unplaned	.011	.013*	.014	.015
With battens	.012	.015*	.016	
Concrete-lined channels	.012	.014*	.016*	.018
Cement-rubble surface	.017	.020	.025	.030
Dry-rubble surface	.025	.030	.033	.035
Dressed-ashlar surface	.013	.014	.015	.017
Semicircular metal flumes, smooth	.011	.012	.013	.015
Semicircular metal flumes, corrugated	.0225	.025	.0275	.030
Canals and Ditches:				
Earth, straight and uniform	.017	.020	.0225*	.025
Rock cuts, smooth and uniform	.025	.030	.033*	.035
Rock cuts, jagged and irregular	.035	.040	.045	
Winding sluggish canals	.0225	.025*	.0275	.030
Dredged earth channels	.025	.0275*	.030	.033
Canals with rough stony beds, weeds on earth banks	.025	.030	.035*	.040
Earth bottom, rubble sides	.028	.030*	.033*	.035
Natural Stream Channels:				
(1) Clean, straight bank, full stage, no rifts or deep pools	.025	.0275	.030	.033
(2) Same as (1), but some weeds and stones	.030	.033	.035	.040
(3) Winding, some pools and shoals, clean	.033	.035	.040	.045
(4) Same as (3), lower stages, more ineffective slope and sections	.040	.045	.050	.055
(5) Same as (3), some weeds and stones	.035	.040	.045	.050
(6) Same as (4), stony sections	.045	.050	.055	.060
(7) Sluggish river reaches, rather weedy or with very deep pools	.050	.060	.070	.080
(8) Very weedy reaches	.075	.100	.125	.150

From *Handbook of Hydraulics*, by King, McGraw-Hill Book Company.

* Values commonly used in designing.

5
Pumping Water for Irrigation

There are large areas of arable land in arid regions so situated that available water cannot be brought to them by gravity. Other areas may be reached by gravity but the locations and topography with respect to the water supply are such that cost of building the necessary gravity canals, flumes, inverted siphons, tunnels, and other conveyance structures is so great that water cannot be provided economically. For many of these areas, water is raised by some mechanical device from its natural sources, whether surface or underground, to the elevation of the higher parts of the land, or to still higher elevations if at distant points, so that it will flow over the land by gravity for irrigation purposes. This practice of raising water, known as irrigation pumping, is widely followed in the arid regions of the world. In the humid regions of the United States pumping is becoming an important practice for irrigation by sprinkling.

The mechanical devices for lifting water for irrigation vary widely. Some are crude and inefficient; others are highly perfected and efficient. This chapter is concerned with the principles and problems of pumping water in relatively small quantities for individually owned farms. It does not include the engineering problems involved in the design and operation of the large irrigation pumping projects, which are as a rule owned by corporate or other community enterprises.

52. Power Requirements and Pumping-Plant Efficiencies Mechanical power is defined as the time rate of doing work, and work is defined as the product of force and distance. The power units commonly used in irrigation are foot-pounds per second and horsepower. To lift 2 cu ft of water (125 lb) a vertical distance of 1 ft per sec would require 125 ft-lb per sec, provided the lifting device (pumping plant) were 100 percent efficient. If the pumping-plant efficiency were only 50 percent it would require 250 ft-lb per sec, thus providing for a loss of one-half of the total required power in overcoming friction and in

generating heat. The unit of power most commonly used in the United States is the horsepower, which is 550 ft-lb per sec, or 33,000 ft-lb per min. One horsepower would lift 1 cfs a vertical distance of 8.8 ft if it were possible to get 100 percent efficiency as shown below:

$$\text{Horsepower} = \frac{1 \times 62.5 \times 8.8}{550} = 1$$

Because it is impossible to obtain an efficiency of 100 percent the horsepower required to lift 1 cfs any height, as illustrated above, is designated the "theoretical horsepower."

Pumping-plant efficiency is defined as the ratio of the power output to the power input. The electricity, gas, oil, or coal consumed by the motor or engine is the input. Table 12, taken from *New Mexico Agr. Exp. Sta. Bul.* 237, shows actual horsepower requirements for streams from 0.22 to 3.34 cfs, and pumping lifts from 10 to 80 ft, with a 50 percent pumping-plant efficiency. To determine the horsepower required for lifting a stream of any size to a given elevation the reader need only multiply the observed value for 1 cfs in the table by the size of stream selected. For example, Table 12 shows that to lift 1 cfs 40 ft would require 9.09 hp. Therefore, 5 cfs would require 45.45 hp for a 40-ft lift. To obtain the theoretical horsepower, multiply the actual requirement of 45.45 hp by the efficiency, expressed as a decimal.

$$\text{Theoretical hp} = 0.50 \times 45.45 = 22.72$$

The horsepower delivered by an electric motor or by an engine to the shaft it turns is known as the brake horsepower. The ratio of the useful water horsepower delivered by a pump (the output) to the brake horsepower (the input to the pump) is defined as the pump efficiency.

To understand clearly the consumption of different fuels in pumping, it is helpful to note that, by definition,

$$\text{Power} = \frac{\text{Work}}{\text{Time}} \tag{22a}$$

and hence that

$$\text{Work} = \text{Power} \times \text{Time} \tag{22b}$$

The expression horsepower-hour is used to designate the continuous consumption or delivery of 1 hp for a period of 1 hour, and is therefore equal to 550 × 60 × 60 ft-lb of *work*.

TABLE 12

HORSEPOWER REQUIRED TO LIFT DIFFERENT QUANTITIES OF WATER TO ELEVATIONS OF 10 TO 80 FT

(Efficiency of pumping plant 50 percent of theoretical. Use for estimating only.)
(*N. Mex. Agr. Exp. Sta. Bul.* 237)

Gallons per Minute	Cubic Feet per Second	Horsepower Required for Elevations of							
		10 ft	20 ft	30 ft	40 ft	50 ft	60 ft	70 ft	80 ft
100	0.22	0.50	1.01	1.52	2.02	2.53	3.03	3.54	4.04
150	0.33	0.76	1.52	2.27	3.03	3.79	4.55	5.30	6.06
200	0.45	1.01	2.02	3.03	4.04	5.05	6.06	7.07	8.08
250	0.56	1.26	2.53	3.79	5.05	6.31	7.58	8.84	10.10
300	0.67	1.52	3.03	4.55	6.06	7.58	9.09	10.61	12.12
350	0.78	1.77	3.54	5.30	7.07	8.84	10.61	12.37	14.14
400	0.89	2.02	4.04	6.06	8.08	10.10	12.12	14.14	16.16
450	1.00	2.27	4.55	6.82	9.09	11.36	13.64	15.91	18.18
500	1.11	2.53	5.05	7.58	10.10	12.63	15.15	17.68	20.20
600	1.34	3.03	6.06	9.09	12.12	15.15	18.18	21.21	24.24
700	1.56	3.54	7.07	10.61	14.14	17.68	21.21	24.75	28.28
800	1.78	4.04	8.08	12.12	16.16	20.20	24.24	28.28	32.32
900	2.01	4.55	9.09	13.64	18.18	22.73	27.27	31.82	36.36
1,000	2.23	5.05	10.10	15.15	20.20	25.25	30.30	35.35	40.40
1,250	2.78	6.31	12.63	18.94	25.25	31.57	37.88	44.19	50.50
1,500	3.34	7.58	15.15	22.73	30.30	37.88	45.45	53.03	60.61

The "water horsepower" is defined as the power theoretically required to lift a given quantity of water per second to a specified height. In irrigation pumping it may be termed the "output." Then

$$hp_w = \frac{62.5Qh}{550} = \frac{Qh}{8.8} \tag{23}$$

where hp_w = water horsepower;
Q = discharge in cubic feet per second;
h = vertical lift in feet.

If Q is measured in gallons per minute rather than cubic feet per second then

$$hp_w = \frac{8.33Qh}{33,000} = \frac{Qh}{3960} \tag{24}$$

Equations 23 and 24 are useful in determining water horsepower when Q and h are known. Based on the definition given above,

$$\text{Pumping-plant efficiency } E_p = \frac{Qh}{8.8 \times \text{Horsepower input}} \tag{25}$$

Occasional field tests of plant efficiencies aid the irrigator to guard against low efficiencies and expensive operation.

Field tests have been made by Johnston of the efficiencies of 91 irrigation pumping plants in California. The results of these tests show averages of 49.8 percent for centrifugal pumps, 40.5 percent for deep-well turbine pumps, and 44.5 percent for deep-well screw pumps. The maximum plant efficiency found was 70 percent and the minimum 15.2 percent. It is important to the farmer to keep pumping equipment in good condition. Low efficiencies are largely chargeable to failure on the part of pump owners to keep equipment in good running order.

53. Pumping Lifts The vertical distance through which water is lifted for irrigation purposes varies widely. In some localities, notably in parts of Egypt and of India, the water is lifted only a few feet; in other places, like parts of California, it is raised several hundred feet. In American irrigation practice the maximum height of lift is determined by cost limitations, not by mechanical or power limitations. From the discussion of Article 52, and from Table 12, it is apparent that for any given size of irrigation stream the power requirement is roughly proportional to the lift. The difference in elevation of the water surface in a pond, lake, or river from which the pumped water is taken, and the water surface of the discharge canal, is known as the "static head." In pumping from ground-water sources the static head includes also the "drawdown," which is the head required to drive the same volume of water per second from the soil into the well as is received by the pump and delivered to the surface of the land. It is desirable always to avoid excessive drawdown in order to reduce excessive power requirements. In addition to the static head that pumps must work against, consumption of a certain amount of power is essential to drive a given stream against the frictional resistance, sharp curves in pipes, and other factors that retard water motion. These retardation elements explain the fact that pumping-plant efficiencies range from about 75 percent under very favorable conditions down to 20 percent or even less under unfavorable conditions.

In Utah and Idaho, under general farm practice, it is rarely profitable to pump water for irrigation purposes against a static head in excess of 75 ft. In parts of the Pacific coast states under intensive agriculture, water is economically pumped for irrigation against static heads of 300 ft or more. Because of the large number of variable factors influencing profits from pumping water for irrigation, it is impracticable to set specific limits of profitable pumping lifts that will apply in different localities for any length of time. It is important for farmers

who contemplate irrigation pumping to keep in mind the fact that cost to the farmer of pumped water is roughly proportional to the height of lift. Proposals to pump water through high lifts should be carefully considered before investments are made; on the other hand, good

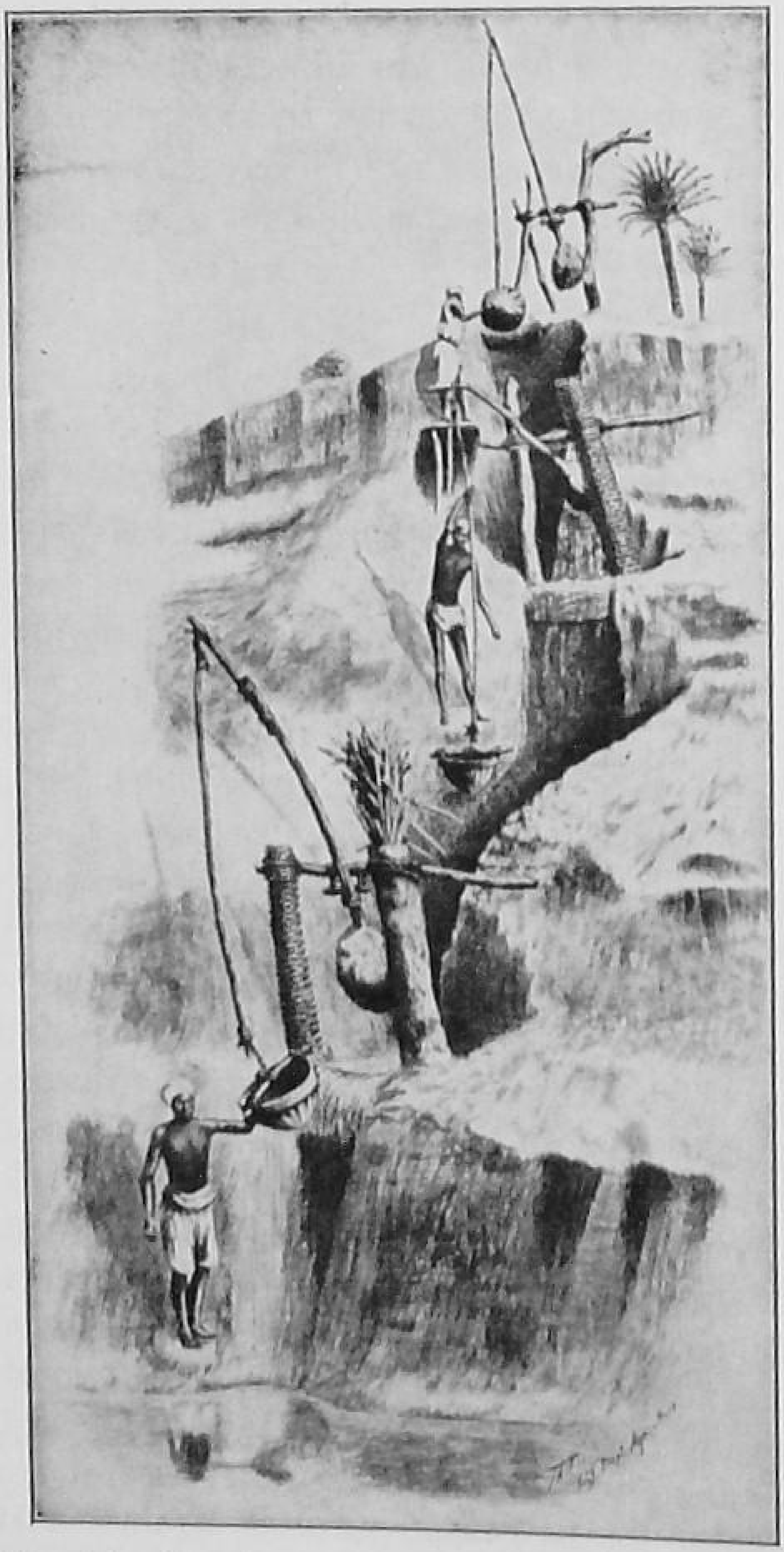


FIG. 47. The shaduf. (*U.S.D.A. O.E.S. Bul.* 130.)

dependable water supplies that may be made available for irrigation by pumping only a few feet should not be overlooked.

54. Primitive Irrigation Pumping Methods Raising water for irrigation has been practiced for centuries in Egypt, India, and others of

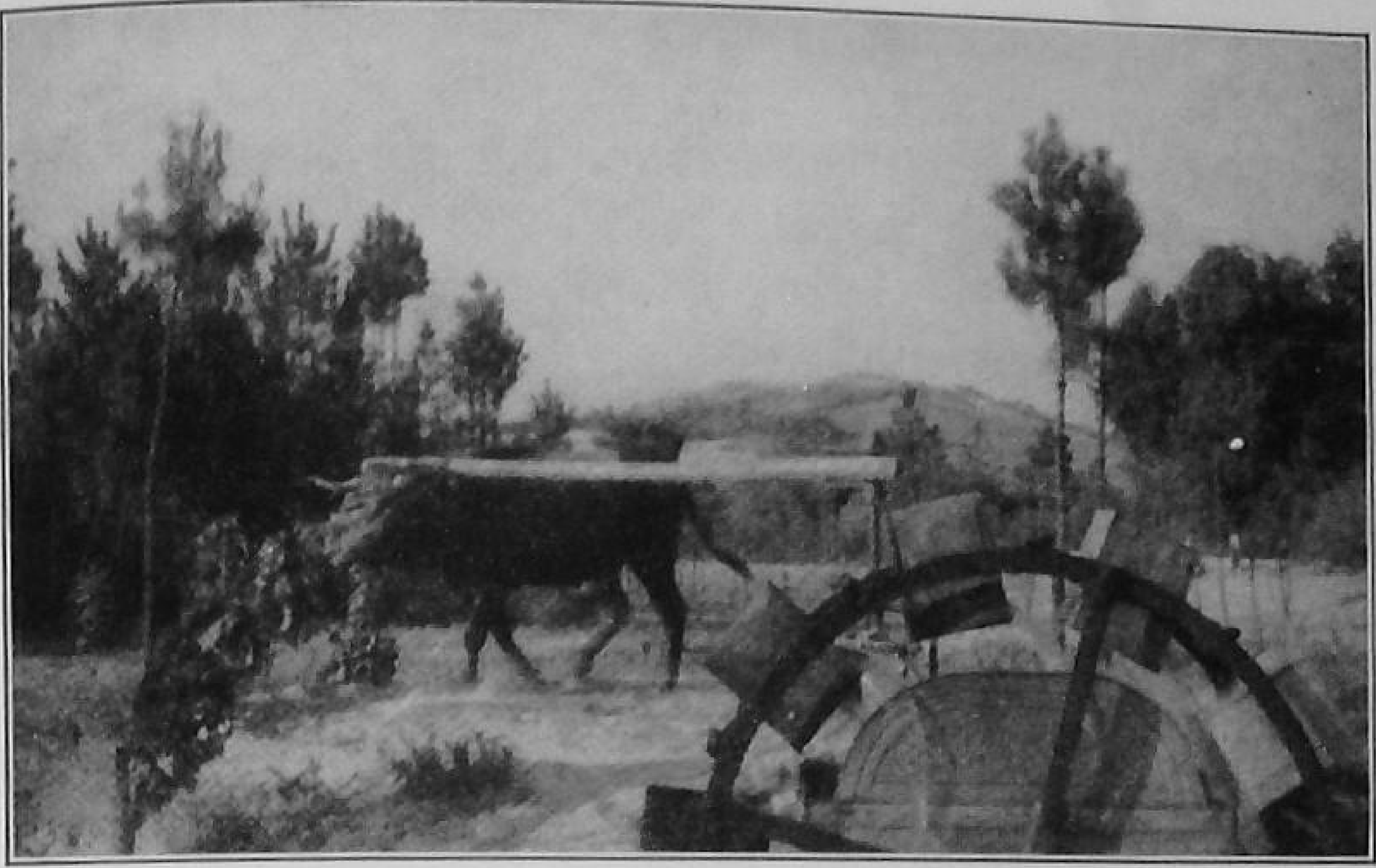


Fig. 48. Typical Portuguese pumping plant. The ox on a circular path is blindfolded and unattended. (Photograph by Lettie Rodrigo.)

the older countries where irrigation is essential to agriculture. One of the devices early used in Egypt and India, known as the shaduf, is illustrated in Fig. 47. This device makes use of the principle of the lever with a suspended fulcrum and a counterweight. The bucket, suspended from the long end of the pole, is sometimes made of leather, stiffened near the top with a wooden hoop. The operator throws his weight on the sweep, the bucket fills, and the counterweight raises it to the next higher channel into which the water is poured. A single shaduf is operated by one man, and with it he can lift water only 5 or 6 ft, but the devices are sometimes installed in series of three or four, thus raising the water 20 ft or more. With the shaduf one man can raise approximately 22 gpm from 5 to 6 ft, thus attaining an efficiency of about 25 percent.

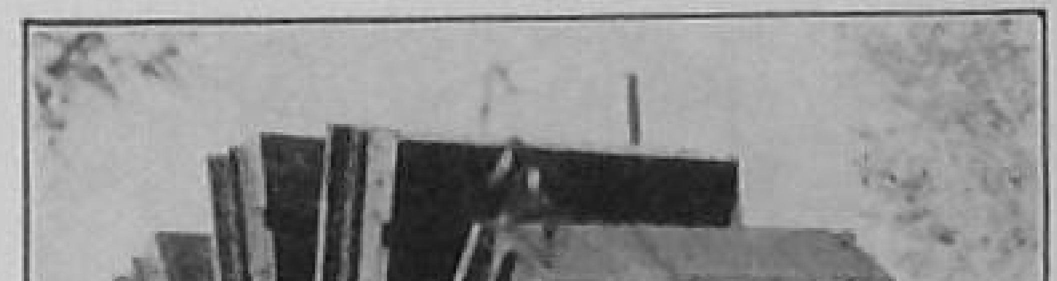


Fig. 49. Showing 22-foot-diameter steel water wheel delivering 1.5 cfs to ditch 11 ft above main ditch. Near Littlefield, Arizona. (November 1940.)

Another primitive device, a water wheel turned by man or animal, illustrated in Fig. 48, was photographed in Portugal in 1947. A larger and more efficient water wheel 22 ft in diameter driven by waterpower and lifting water 11 ft is shown in Fig. 49.

55. Modern Irrigation Pumping Methods In contrast to the primitive methods of pumping water for irrigation, pumping machinery of high efficiency is used on many irrigated farms. In the western United States substantial advancement has been made in the design and operation of pumps. Pumping costs are greatly reduced by obtaining the necessary energy for pumping from coal, gasoline, crude oil, or electricity rather than using the energy of man or of animals. To illustrate, assume that for irrigation pumping 1 kw-hr of electric energy may be purchased at a cost ranging from 1 to 3 cents. As 1 kw-hr equals approximately $\frac{4}{3}$ hp-hr, 1 hp-hr on the basis of 1 to 3 cents per kw-hr would cost $\frac{3}{4}$ to $2\frac{1}{4}$ cents. A strong healthy man, in an hour, can generate about $\frac{1}{8}$ hp-hr work. At the rates of 60 to 90 cents per hour for man labor the cost of 1 hp-hr would range from 480 to 1440 cents as compared to $\frac{3}{4}$ to $2\frac{1}{4}$ for electricity.

Modern irrigation pumping methods are based on years of painstaking laboratory research, together with careful study of field pumping conditions by competent engineers. Out of these investigations there have come into use pumps of different classes and types, each suited to the different demands and conditions of operation. Typical modern irrigation pumps of different types are briefly described in Articles 58 to 61.

56. Pump Characteristics In order to use modern pumps most profitably to obtain irrigation water, it is essential to select pumps well adapted to the particular conditions of operation and to obtain a relatively high efficiency. If the quantity of water pumped is appreciably less than the quantity for which the pump is designed, and the head is excessive, a low efficiency results. Likewise, a pump may deliver more water than it is designed for at a head lower than normal and cause the efficiency to be low. The interrelations between speed, head, discharge, and horsepower of a pump are usually represented by curves which are designated the "characteristic" curves. Knowledge of the characteristics of a pump enables the manufacturer and irrigator to make adaptations of the pump to the operating conditions and thus attain a relatively high efficiency and low operating cost. The characteristics of a standard horizontal-shaft centrifugal pump are shown in Fig. 50. These curves show, for example, that, for quantities ranging from 700 up to 1440 gpm at heads ranging from 105 ft down to 65 ft, the efficiency of the pump will be equal to or greater than 70 percent; also that it will attain a maximum efficiency of 82 percent at quantities from 1100 to 1200 gpm and at a head of approximately 90 ft.

57. Types of Pumps Pumps for irrigation purposes are of many different makes. Those most commonly used may be grouped into

three types: namely, centrifugal, deep-well turbine, and reciprocating or plunger pumps. Air-lift pumps are sometimes used to develop wells, but because of low efficiency they are rarely employed for permanent pumping operations. Brief descriptions of the distinguishing mechanical features of each of the first two types, and of their types of impellers, are given in the following sections, after which the plunger pumps are discussed.

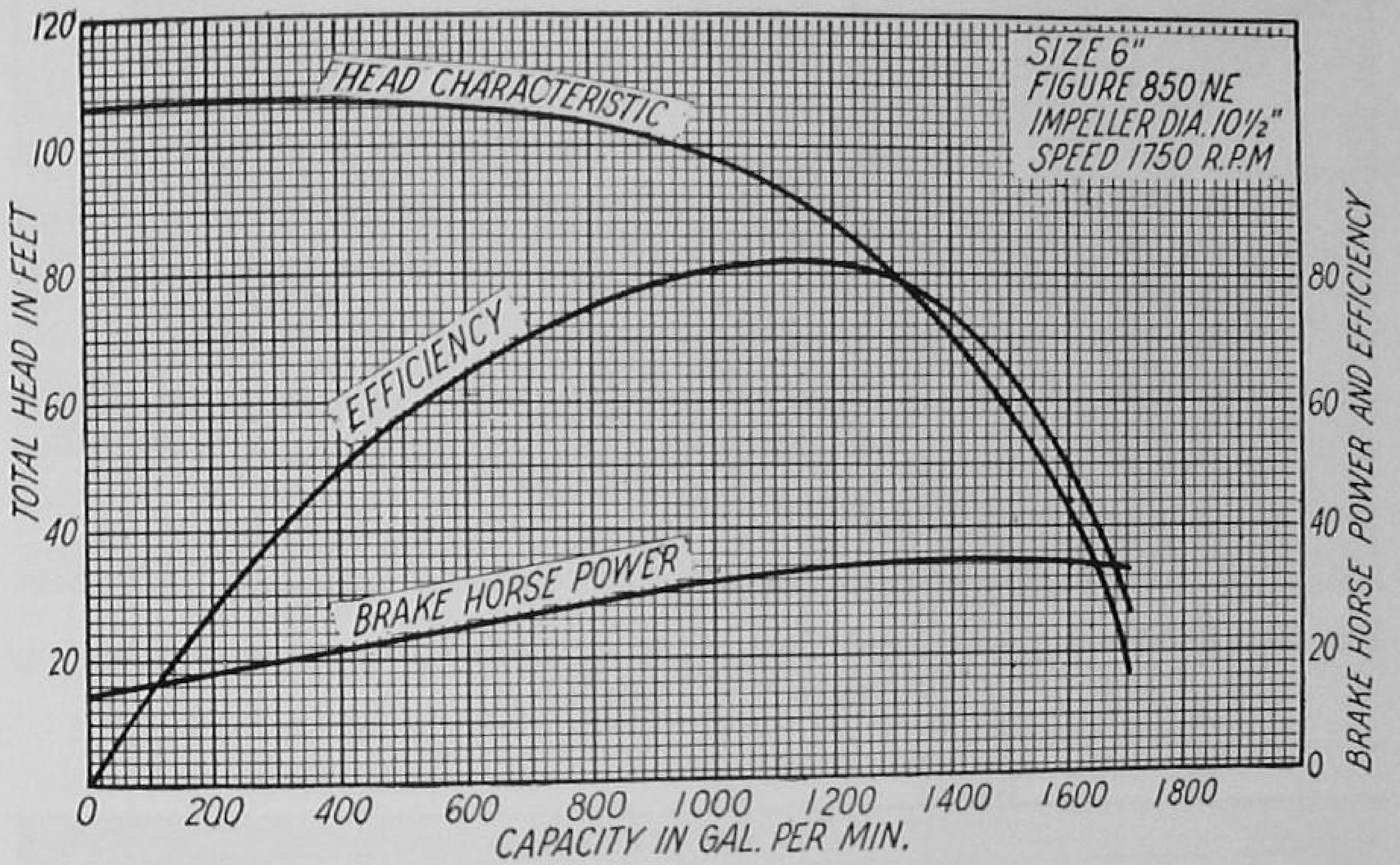


FIG. 50. Characteristic performance curves from test records. (Courtesy Fairbanks-Morse Company.)

58. Centrifugal Pumps A centrifugal pump consists of a rotating impeller within a casing into which water enters at the center of the side and flows outward. The pump imparts energy to the water in the form of increased velocity and pressure. There are two classes of centrifugal pumps: the volute and the turbine. The essential point of difference in the two classes is the construction around the impeller. The turbine centrifugal pump has fixed diffuser vanes in order to convert velocity energy into pressure energy more efficiently. Centrifugal pumps are built both on horizontal and on vertical shafts. When driven by electric power they are generally connected directly to the shaft of the motor, provided that the proper speed can be attained. Centrifugal pumps vary in capacity from a very few gallons per minute up to 300 cfs or more. For farm irrigation purposes the pumps most commonly used vary from ⅕ to 5 cfs in capacity. A horizontal-shaft single-stage split-case volute centrifugal pump direct-connected to an electric motor is illustrated in Fig. 51.

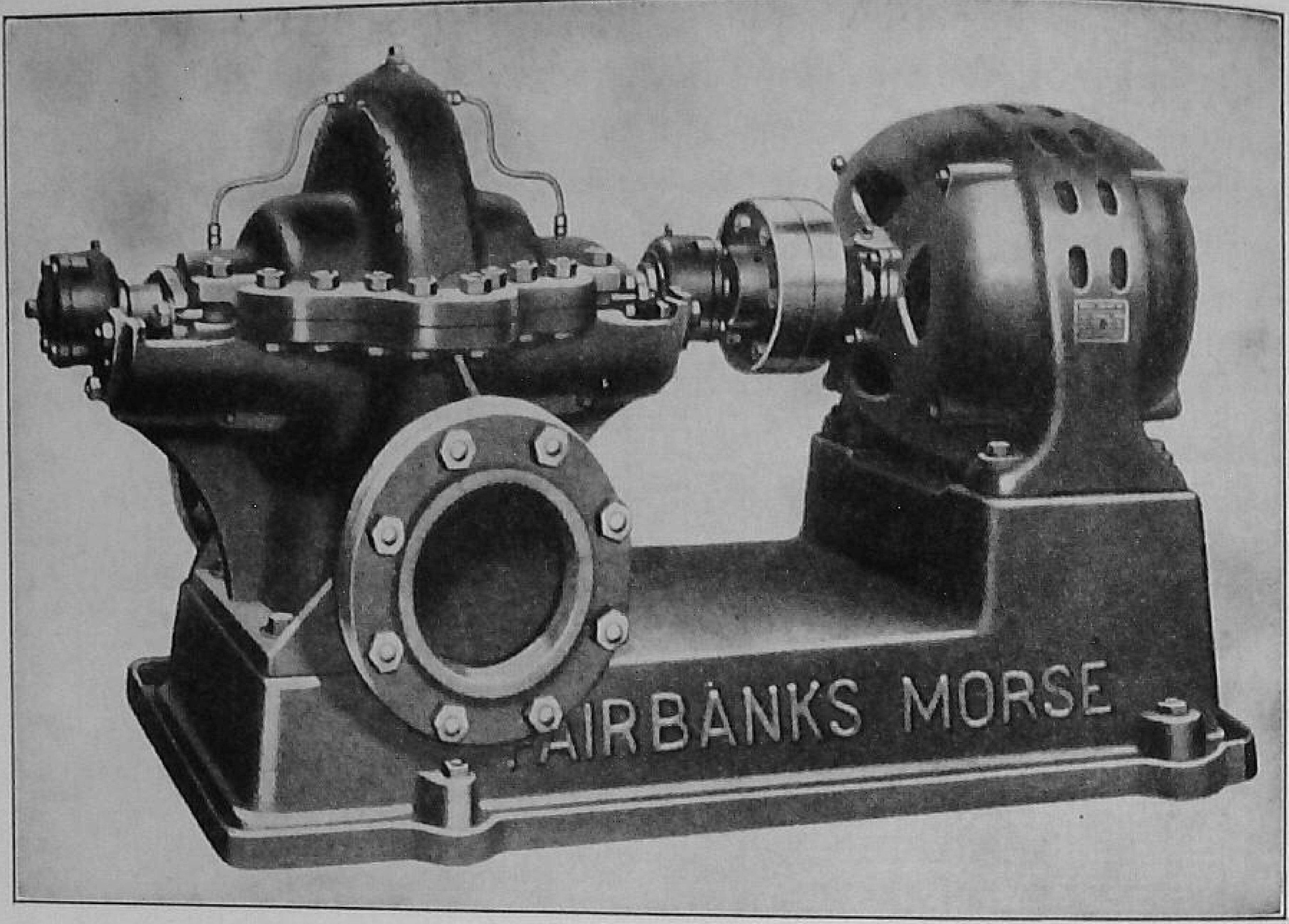


Fig. 51. Ball-bearing centrifugal pump direct-connected to a motor. (Courtesy Fairbanks-Morse Company.)

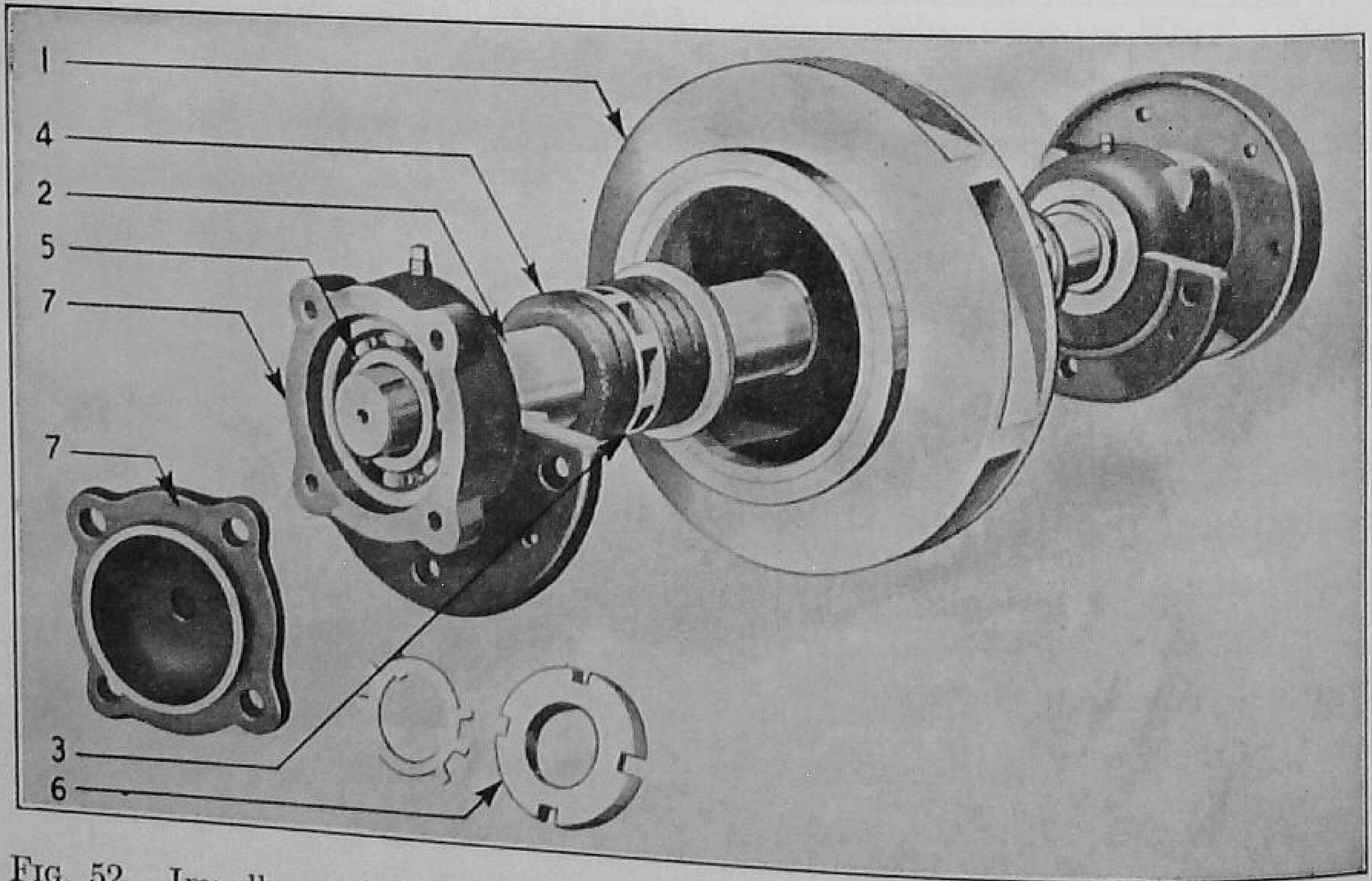


Fig. 52. Impeller and shaft assembly of pumps showing: (1) enclosed impeller; (2) ground carbon-steel shaft; (3) water seal ring; (4) packing; (5) standard ball bearing; (6) lock nut; and (7) ball-bearing housing and cover. (Courtesy Fairbanks-Morse Company.)

Horizontal-shaft centrifugal pumps are set above the surface of the water to be pumped and hence are dependent on the atmospheric pressure to force water up to the pump. To start these pumps it is necessary to fill the suction pipe and pump case with water and thus expel all the air. This operation of filling suction and pump case is designated "priming the pump." It is usually advantageous to set the pump as near the water surface as convenient and yet protect it from submergence during high water. It is important to avoid submergence of pumps that are direct-connected to electric motors. The maximum vertical working distance from water surface to pump at sea level is about 25 ft. At higher elevations a proportionately less maximum distance must be provided. The horizontal-shaft centrifugal pumps are relatively free from trouble, have high efficiencies, stand high speeds, and are conveniently direct-connected to electric motors. The pump operates at a speed of 1750 rpm. This shaft and impeller together with other detail parts of the pump shown in Fig. 51 are illustrated in Fig. 52.

59. Deep-Well Turbine Pumps In order to obtain water economically from deep, small-diameter, machine-constructed wells, modern deep-well turbine centrifugal pumps have been developed and greatly improved. The rotating impeller is built on a vertical

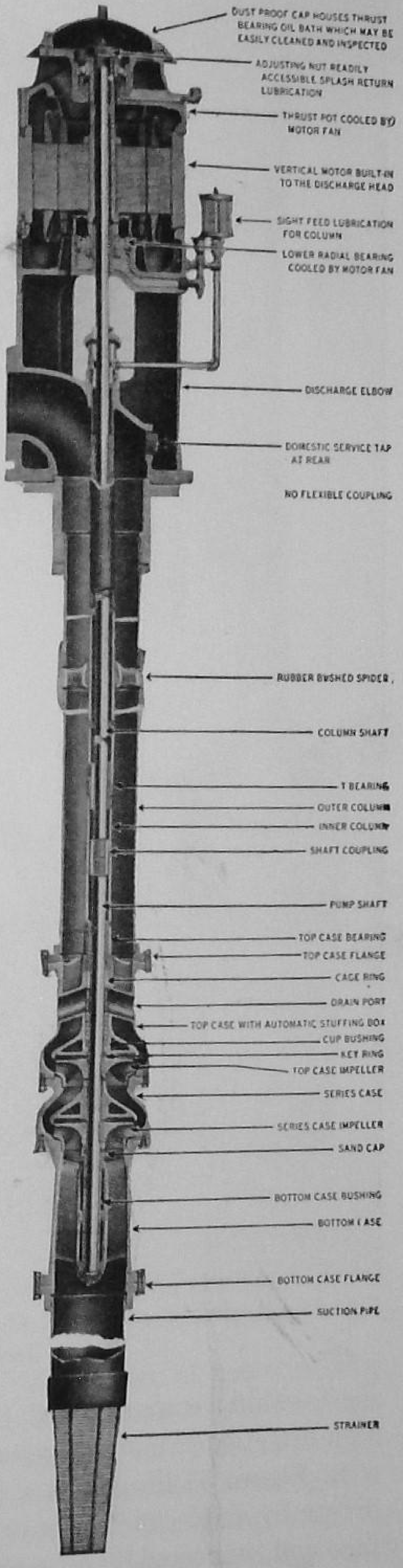


Fig. 53. Cutaway section of two-stage Byron Jackson deep-well turbine pump and motor showing details of parts. (Courtesy Byron Jackson Company.)

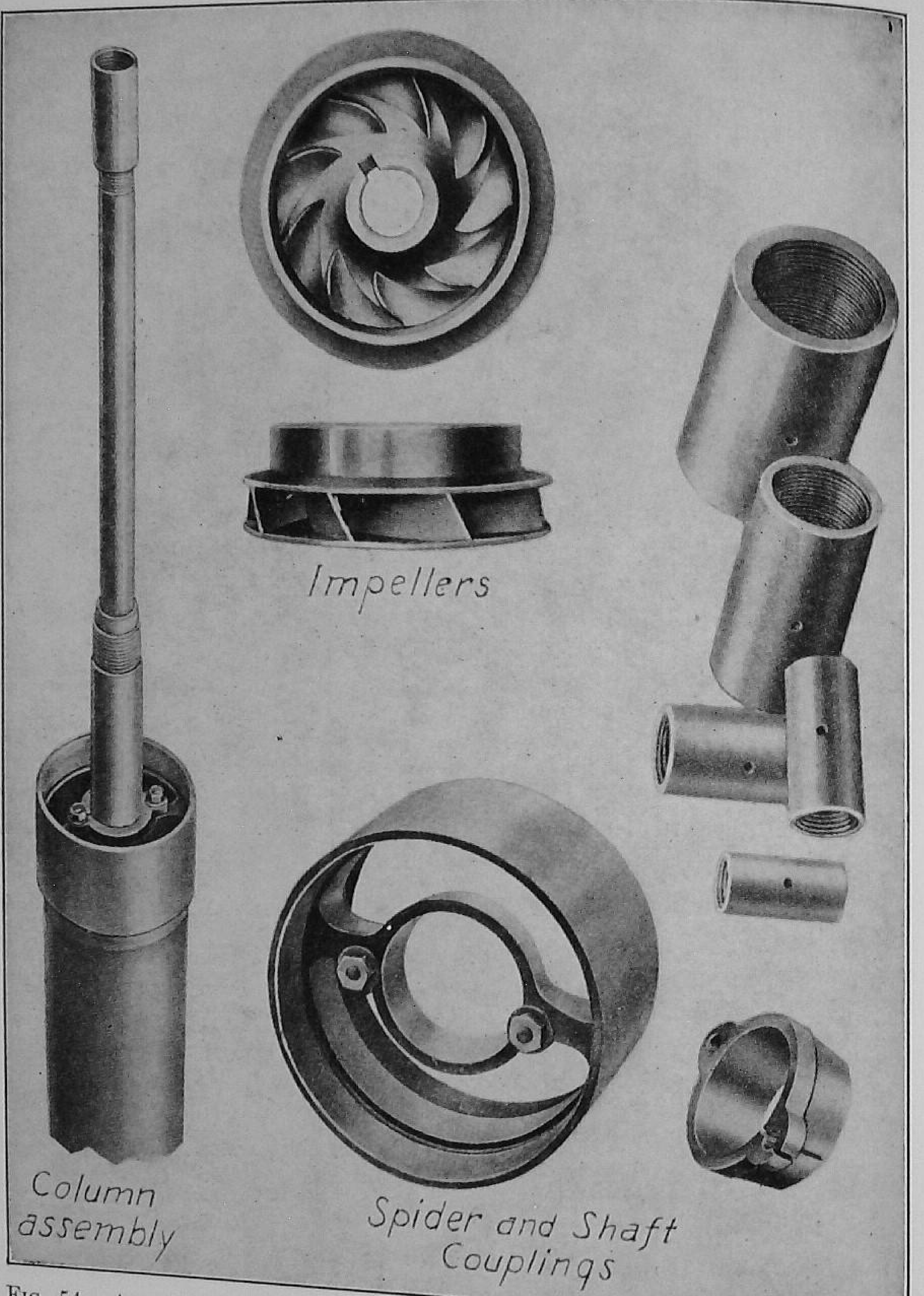


FIG. 54. Assembly and parts of a deep-well turbine pump. (Courtesy Byron Jackson Company.)

shaft within a compact bowl, the entire unit being known as a stage. For high lifts, two or more stages are placed in series near the bottom of the well. Figure 53 illustrates a two-stage deep-well pump. The pump is driven by an electric motor or other prime mover set at the ground surface and connected by a long vertical shaft held in position by bearings

built in the discharge pipe or column. Being submerged, the deep-well pumps have the advantage of requiring no priming and of meeting rather wide fluctuations of water surface without necessitating a

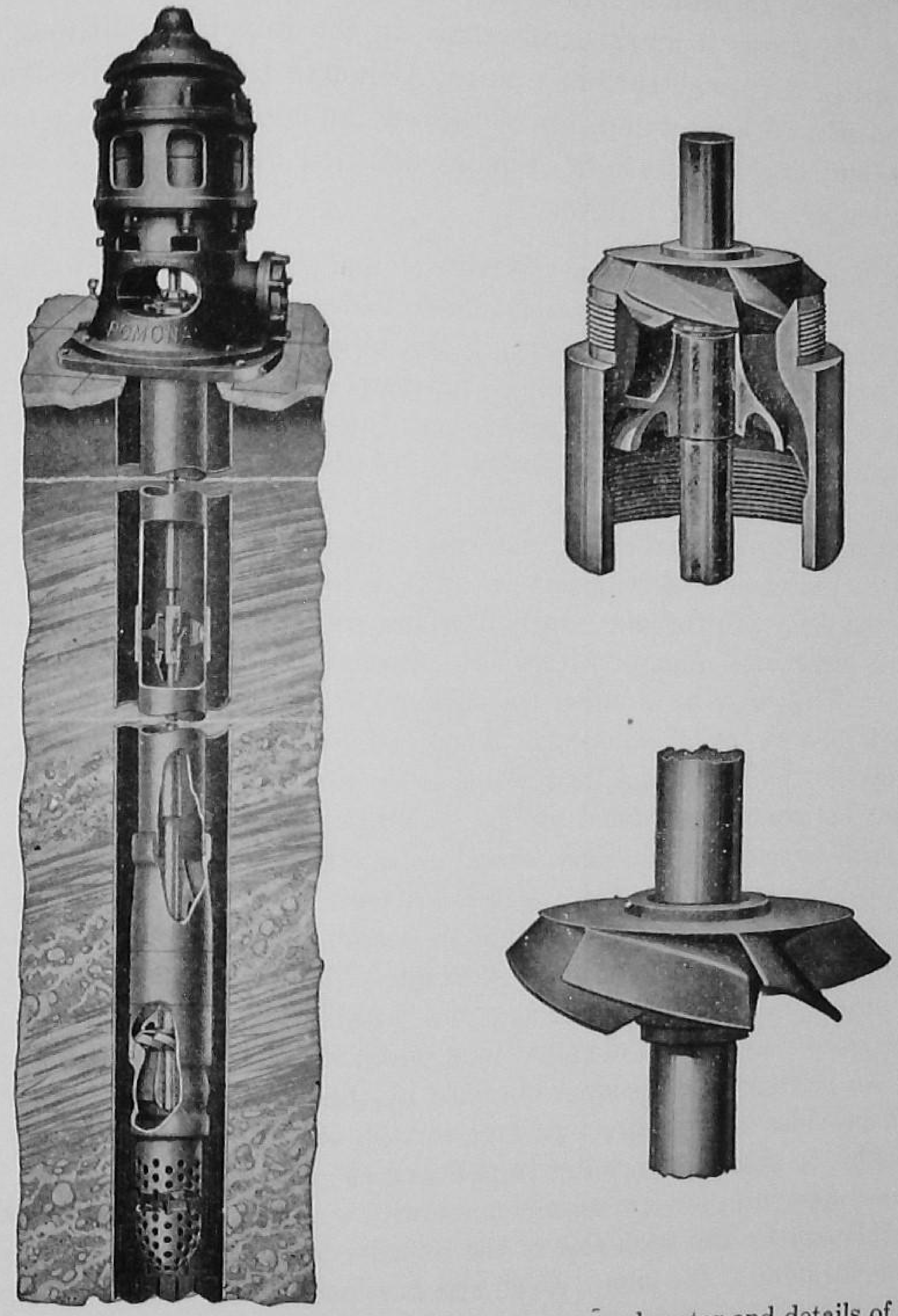


Fig. 55. Cutaway section of Pomona turbine pump and motor and details of bowl and impeller keyed to shaft. (Courtesy Pomona Pump Company.)

resetting of the pump. They have the disadvantage of inaccessibility of operating parts and consequent difficulty of inspection. Low efficiencies are more common than with horizontal-shaft pumps, because the deep-well pumps are frequently permitted to continue running after bearings are worn badly and sometimes until the pump fails to operate before repairs are provided. Figure 54 illustrates the several

parts of a deep-well pump, showing also the position of the shaft and the column.

60. Types of Impellers Another form of deep-well pump, illustrated in Fig. 55, shows a marked difference in the impellers, although both are used in deep-well turbine pumps. Although the pump illustrated in Fig. 55 is a turbine pump, the semiopen impeller resembles somewhat the screw type of impellers. A more detailed description of impellers presented by Rohwer follows:

The horizontal and vertical centrifugal and the true deep-well turbine operate on the centrifugal principle. The mixed-flow turbine is a combination of the centrifugal and the propeller types, in which the action of the pump is the result of a combined centrifugal force and direct thrust. In the axial-flow propeller or screw-type pump there is very little centrifugal action, the water being moved by the thrust of the blades of the propeller. Impellers of the different types are shown in Fig. 56.

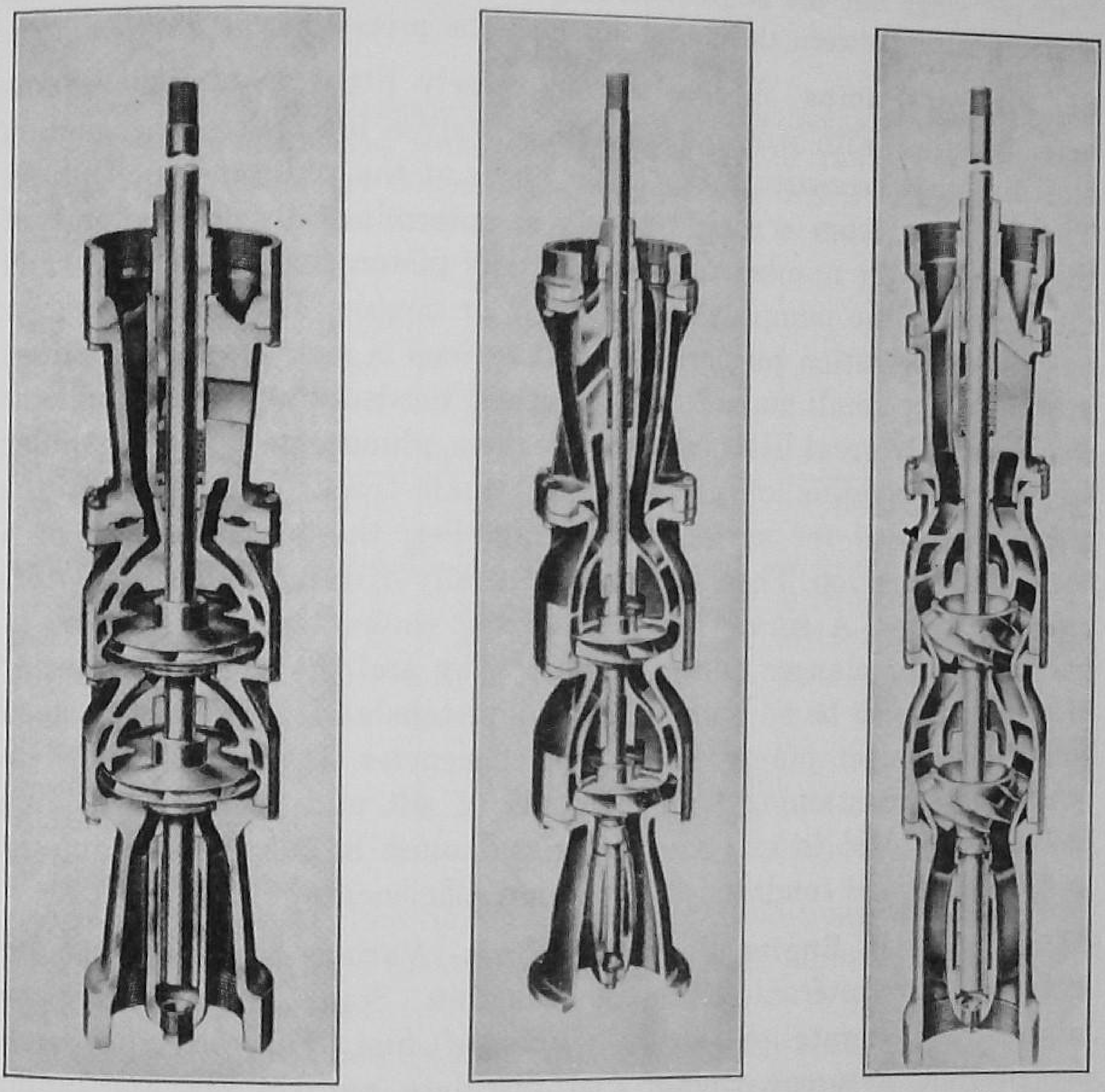
Centrifugal-type impellers are either enclosed, semienclosed, or open. Enclosed and semienclosed impellers are used in horizontal and vertical centrifugals and deep-well turbines. Open impellers are found only in horizontal and vertical centrifugal pumps. Mixed-flow impellers are used only in deep-well turbines. They may be of either the enclosed or semienclosed types (Fig. 56*A* and 56*B*). Screw- or propeller-type impellers are with shrouds. They are similar to propellers on boats, and their action is the same.

Most horizontal centrifugal pumps for irrigation have semienclosed impellers; some have closed impellers. Closed impellers are found mostly in the more expensive double-suction pumps such as are used in municipal pumping plants. They are also the most common type in deep-well turbines. Since the size of the impeller in deep-well turbines is definitely limited by the diameter of the well, it sometimes happens that it is not possible to obtain the full capacity from a good well of small diameter by a pump with impeller of the centrifugal type. An increase in capacity is obtained by the use of a mixed-flow impeller, which provides a more direct passage for the water and consequently makes it possible to obtain more water from a well of given diameter.

Mixed-flow impellers are usually made with semienclosed vanes, as shown in Fig. 56*B* and *C*. The open side of the impeller is turned accurately to fit the seat in the bowl of the pump, which also is accurately machined. The capacity of pumps with semienclosed impellers can be decreased by raising the impeller in the event that the flow of the well decreases. This adjustment causes a reduction in the efficiency of the pump, but it is not as great as it would be if the capacity were reduced by throttling the discharge.

Enclosed impellers of the centrifugal type have a circular skirt attached to the bottom shroud which fits into an annular space in the pump bowl called the sealing ring (Fig. 56*A*). Both these surfaces are accurately machined so as to obtain a close-running fit because the seal at this ring prevents the water from leaking from the discharge side of the impeller back to the suction side.

Since the difference in pressure is large there is always some leakage, and, if the water carries sand, the parts wear rapidly. This wearing results in a considerable part of the water leaking back through the sealing ring. When sand is especially troublesome stainless-steel or hard-bronze rings are fitted



A *B* *C*

Fig. 56. Section of two-stage deep-well turbine bowls: *A*, with impellers of the centrifugal type; *B*, with semienclosed impellers of the centrifugal type; and *C*, with mixed-flow impellers, a combination of axial-flow and centrifugal types. (*U.S.D.A. Circ.* 678.)

to the skirt for the purpose of reducing the wear. At this point a double seal is sometimes used. This consists of a rubber ring set into the bowl so that it is just below the bottom edge of the skirt of the impeller. By lowering the impeller a small clearance can be maintained even though there is considerable wear caused by the sand. It is important that sufficient clearance be maintained so that the impeller does not rest on the rubber seal ring, lest there be considerable loss of power due to the friction and injury to the rubber ring.

Impellers of the centrifugal type produce a high head per stage, but the

quantity pumped is small. This is the type of impeller used on high-head installations where the diameter of the well is large enough to accommodate an impeller of the required diameter. Mixed-flow impellers produce a medium head per stage, and screw- or propeller-type impellers produce the smallest head per stage but the largest discharge. An intermediate-type impeller has characteristics between the mixed-flow and the propeller-type impeller.

61. Plunger Pumps Sliding pistons closely fitted in airtight chambers, together with suitable automatic valves for controlling suction and discharge, constitute the basic parts of the plunger-type pumps. The capacity from a single piston is determined by the volume of the chamber, the number of movements of piston per unit of time, and the action of the pump, whether single or double. The use of plunger pumps for irrigation purposes in arid regions is restricted to localities in which only small amounts of water are needed and are available at comparatively great lifts. In humid regions, plunger pumps are popular for spray irrigation of gardens and small truck farms. When the pumps are used for surface water supplies, the piston moves in a horizontal direction. These pumps are usually driven by electric motors or gas engines. A survey in New Jersey shows the average size of gas engine for plunger pumps to be 6½ hp and the average capacity of each pump to be 85 gpm. When the pistons and valves are in good condition plunger pumps have high efficiencies. If they are used to pump water containing large amounts of silt and sand, the moving parts are subject to excessive wear and must be inspected regularly and kept in good condition to avoid low efficiencies.

62. Combustion Engine Fuels and Costs Various types of fuel are available for internal-combustion engines. Some engines may be adapted to operate on several types of fuel. The principal ones are gasoline, kerosene, tractor fuel, distillate, natural gas, and liquid gas. Costs of these fuels vary considerably, depending on the location of the source of supply with reference to the pumping plant, freight rates, and taxes. The kind of fuel that is most economical depends on its cost and the power produced per unit of fuel, and on the cost of the type of engine required. Distillate is low in price and the fuel consumption of Diesel engines is low, but the cost of a Diesel engine is more than twice that of a gasoline or natural-gas engine of equal power.

The amount of fuel consumed per horsepower-hour by an engine in good condition and proper adjustment depends on the kind of fuel, the altitude, the temperature, and the speed, and on whether or not the engine is fully loaded. The consumption of different kinds of fuel per brake horsepower-hour at sea level when the air temperature is

60° F and when the engine is completely equipped and fully loaded is set out in Table 13. The fuels listed are mixtures of hydrocarbons in some cases of widely varying composition. Consequently, it is important to note that the values given for their properties are based

TABLE 13

CONSUMPTION OF DIFFERENT KINDS OF FUEL PER BRAKE HORSEPOWER-HOUR AT SEA LEVEL WHEN THE TEMPERATURE OF THE AIR IS 60° F AND ENGINE IS COMPLETELY EQUIPPED AND FULLY LOADED, AND OTHER PERTINENT DATA (USDA Circular 678)

Fuel	Weight per Gal	Density	Heating Value		Fuel Required per Brake Hp-Hr		
			Per Lb	Per Cu Ft			
	Lb	°B	Btu	Btu	Lb	Gal	Cu Ft
Gasoline	6.0–6.3	59	20,750±	.....	0.60–0.64	0.10	....
Kerosene	6.8	41	19,800	.....	0.72–0.75	0.09	....
Distillate tractor fuel	7.0	37	19,700	.....	0.72–0.75	0.095	....
Fuel oil	7.0–7.6	24–27	19,300±	.....	0.48–0.50	0.07	....
Butane (liquid)	4.7–4.8	115	21,000±	.....	0.41–0.51	0.10	....
Butane (gas)	.....	....	....	3,200±	.....	.....	3.0
Natural gas	.....	....	....	950–1,150	.....	.....	12.5
Manufactured gas	.....	....	....	500–800	.....	.....	15.0

on tests of new engines under laboratory conditions and may vary considerably. For field installations they should probably be increased by at least 10 percent.

The power developed by an electric-ignition internal-combustion engine decreases about 3 percent for each 1000 ft rise in elevation above sea level and about 1 percent for each 10° F rise in temperature above 60° F. By installing high-compression pistons or cylinder heads, a portion of the loss due to altitude can be regained. If air temperatures over 110° F are encountered, provision should be made for cooling the intake manifold. Fuel consumption per brake horsepower increases slightly as the engine speed increases above a certain point, but the power increases almost in direct proportion to the speed. For this reason it is generally desirable, in order to get the additional power, to disregard the slight increase in fuel consumption. Fuel consumption per brake horsepower-hour increases if the engine is not fully loaded. It is not customary to load the engine above 80 percent of its maximum horsepower for continuous operation. If the engine is loaded to only a small proportion of the rated horsepower for the speed, the fuel consumption will be

considerably increased. Under these conditions it will be more economical to reduce the engine speed until the proper horsepower is developed. By changing the pulleys the proper pump speed can be obtained.

To compare the fuel cost per brake horsepower-hour for different kinds of fuel, the fuel consumption shown in Table 13 for the specified fuels should be multiplied by the cost of the fuel. Whichever gives the lowest value will be the most economical from the standpoint of consumption. Other factors, however, such as first cost of equipment, depreciation, or ease of handling, also influence the cost of operation, as shown in Table 14.

63. Electric Service Schedules and Costs Power companies usually base charges for electric service in part on the maximum demand of the consumer, regardless of the energy consumed, and in part on the energy actually used. The purpose of the power company is to encourage consumers to avoid high demands for electricity over short periods of time and to get them to strive to use power as many hours per day and days per month as the conditions may justify. Consideration of a typical power-rate schedule will clarify the low energy costs of low demand and continuous use, as compared to high energy costs resulting from high demand and short-time use.

An irrigation service schedule* provides a monthly power charge of $1.50 per kw for the first 100 kw of demand and $1.00 per kw for all additional kilowatts of demand, which includes no kw-hr. The monthly charge for kw-hr used by the motor is then added to the monthly demand charge, on the following step rate:

1.5¢ per kw-hr first 100 kw-hr per kw of demand
0.9¢ per kw-hr next 5,000 kw-hr
0.6¢ per kw-hr next 20,000 kw-hr
0.4¢ per kw-hr all additional kw-hr

Most irrigation installations are of a permanent nature. Usually, the irrigator signs a 10-yr contract for service which entitles him to a 5 percent term discount on his monthly power bill. Also, when the irrigator makes his original permanent installation, he includes the transformers with his pump and motor installation, which further entitles him to a discount on his monthly power bill, as follows:

20¢ per kw for first 100 kw of demand, and
10¢ per kw for all additional kw of demand

*The service schedule used in these illustrations of electric energy costs is the Utah Power & Light Co. Irrigation and Soil Drainage Pumping, Power Service Schedule 24, which became effective in the State of Utah, April 1, 1948.

Example 1

A 10-hp motor (using a measured demand of 8 kw, for instance) would have a monthly demand charge, whether or not the pump actually runs, provided it was connected to the utilities lines and held in readiness to operate. If the irrigator runs his pump only a few hours per month, for instance 40 hr, the monthly cost would be:

Demand:		
8 kw @ $1.50 per kw	=	$12.00
Energy:		
320 kw-hr @ 1.5c per kw-hr	=	$4.80
Gross charge		16.80
Less term discount, 5%		0.84
Less voltage discount, 8 kw @ 20c		1.60
Net monthly cost		14.36

Average cost per kw-hr = $14.36/320 = 4.45 cents

If the irrigator runs the same pump continuously for 30 days, 24 hr each day, then 720 hr use of the 8 kw demand equals 5760 kw-hr, and his monthly charge would be:

Demand:		
8 kw @ $1.50 per kw	=	$12.00
Energy:		
800 kw-hr @ 1.5c per kw-hr	=	$12.00
4960 kw-hr @ 0.9c per kw-hr	=	44.64
Gross charge		68.64
Less term discount, 5%		3.43
Less voltage discount, 8 kw @ 20c		1.60
Net monthly cost		63.61

Average cost per kw-hr = $63.61/5760 = 1.1 cents

Thus by operating his 10-hp motor 720 hr per month, instead of only 40 hr, the irrigator reduces the unit cost of electricity from 4.45 cents to 1.1 cents per kw-hr, a reduction of 75 percent.

Example 2

For a 200-hp motor, if it runs 40 hr (using a measured demand of 160 kw), the monthly charge would be:

Demand:		
100 kw @ $1.50 per kw	=	$150.00
60 kw @ $1.00 per kw	=	60.00
Energy:		
6400 kw-hr @ 1.5c per kw-hr	=	$96.00
Gross charge		306.00
Less term discount, 5%		15.30
Less voltage discount		
20c for first 100 kw		20.00
10c for next 60 kw		6.00
Net monthly charge		264.70

Average cost per kw-hr = $264.70/6400 = 4.14 cents

If the irrigator runs the same 200-hp motor with a measured demand of 160 kw continuously for 30 days, 24 hr each day, then 720 hr use equals 115,200 kw-hr, and his monthly charge would be:

Demand:			
	100 kw @ \$1.50 per kw	=	\$150.00
	60 kw @ \$1.00 per kw	=	60.00
Energy:			
	16,000 kw-hr @ 1½c per kw-hr	=	\$240.00
	5,000 kw-hr @ 0.9c per kw-hr	=	45.00
	20,000 kw-hr @ 0.6c per kw-hr	=	120.00
	74,200 kw-hr @ 0.4c per kw-hr	=	296.80
	Gross charge		911.80
	Less term discount, 5%		45.59
	Less voltage discount		
	20c for first 100 kw		20.00
	10c for next 60 kw		6.00
	Net monthly charge		840.21

Average cost per kw-hr = \$840.21/115,200 = 0.73 cent

Thus by operating his 200-hp motor 720 hr per month, instead of only 40 hr, the irrigator reduces the unit cost of electricity from 4.14 cents to 0.73 cent per kw-hr, or a reduction of 82.5 percent.

A farmer cannot as a rule use irrigation water continuously to advantage. The advantages in the use of large streams obtained by large motors and pumps partly compensate the irrigator for higher costs for electricity. On the other hand, it is frequently advantageous, where electricity is used for pumping, to provide small reservoirs in which to store the water during the night, thus making it possible to irrigate with a stream approximately twice the size of the pump discharge.

64. Irrigation Pumping Costs In order to estimate the costs of irrigation water obtained by pumping, and to compare these costs with the costs of water from gravity systems, it is customary to compute all pumping costs in terms of the volume of water delivered annually to the irrigated farm. The factors that determine the annual costs of pumped water are:

a. Interest on capital invested in plant, i.e., on first cost.
b. Taxes on plant.
c. Depreciation on pumping machinery and on housing.
d. Fuel or power and lubricating oils.
e. Attendance.

The application of these several factors in arriving at the cost of water obtained by pumping is most clearly presented by working out typical

examples. Two examples have been presented by Code for modern plants designated *A* and *B*. Well *B* cost considerably more than well *A*, and the pump at well *B* has the higher efficiency.

Plant *A* well is 14 in. in diameter and 139 ft deep, the depth of water table being 56 ft. While pumping 2.5 cfs the lift is 77 ft. A turbine pump is driven by a 50-hp high-speed Diesel engine. The costs of 1935 season for pumping 503 acre-feet are presented in Table 14, plant *A*.

Plant *B* well is 48 in. in diameter and 66 ft deep. The water stands at 30 ft normally, and while pumping 2.0 cfs the lift is 55 ft. The equipment consists of a turbine pump direct-driven by a 15-hp motor. The over-all efficiency on test was 65 percent. The costs for the season 1935 in pumping 410 acre-feet are presented in Table 14.

Pumping costs during recent years have increased substantially, but the data of Table 14 illustrate how to determine total costs even with wide variations in unit costs.

In Utah, the customary irrigation company organization is the mutual stock company. One share of stock in many of the companies supplies enough water to irrigate 1 acre of land, from 2 to 3 acre-feet delivered to the farm. Fifty dollars is a common value of stock per share, and $1.50 per share is a common annual stock assessment. On these bases, the annual cost per acre-foot is computed thus:

Interest on $50.00 @ 6%	$3.00
Annual stock assessment (irrigation company water stock is not taxed in Utah)	1.50
Total	$4.50

Average volume of water delivered = 2.5 acre-feet
Cost per acre-foot = $4.50/2.5 = $1.80

A complete or detailed consideration of costs of irrigation water is not within the purpose of this volume, and the above computations are given only for the purpose of illustrating methods of comparisons of cost of water obtained by pumping from wells and water obtained from typical gravity canals.

65. Water Supplies for Irrigation Pumping In the western United States, ground waters form the major source of water supply for small irrigation pumping plants. The methods of drilling and developing wells to obtain ground water are briefly considered in Articles 66 and 70.

In some places the costs of conveying surface water to the farms that need it are greater than the costs of pumping from nearby water supplies. The result is that small pumping plants are used to obtain irrigation water from rivers, canals, ponds, lakes, and other surface sources. A noteworthy example of the use of surface water in irriga-

TABLE 14

COST ELEMENTS FOR TWO MODERN PUMPING PLANTS

(*Colo. Agr. Exp. Sta. Bul.* 433)

Plant A

Cost of Plant:		
Well	$ 600.00	
Pump	840.00	
Engine (installed)	1990.00	
Shelter	75.00	
	$3505.00	
Fixed Charges:		
Interest on $3505.00 @ 5%	$175.25	
Taxes estimated	50.00	
Depreciation on engine 12%	218.88	
Depreciation on pump 8%	67.20	
Depreciation on well and shelter 3%	20.25	
	$531.58	$531.58
Operating Cost:		
Fuel { 470 gal @ $7\frac{1}{2}$c; 5714 gal @ $7\frac{3}{4}$c }	$478.08	
Distillate, 30 gal @ 8c	2.40	
Lubricating oil, 195 gal @ 65c	126.75	
Other oils and greases	13.91	
Sales tax on above @ 2%	12.42	
Engine repairs, anticipated annually	100.00	
Pump repairs, anticipated annually	25.00	
Attendance, 250 hr @ 35c	87.50	
	$846.06	$ 846.06
		$1377.64

Total cost per acre-foot	$2.74
Total cost per acre-foot-foot	0.036
Operating cost per acre-foot	1.68
Operating cost per acre-foot-foot	0.022
Operating time	2487 hr

Plant B

Cost of Plant:	
Well	$1056.00
Pump and motor	1150.00
Shelter	50.00
	$2256.00

TABLE 14 (*Concluded*)

Fixed Charges:		
Interest on \$2256.00 @ 5%	\$112.80	
Taxes estimated	30.00	
Depreciation on pump and motor	92.00	
Depreciation on well and shelter	32.88	
	\$267.68	\$267.68
Operating Cost:		
Electric current, 35,374 kw-hr	\$578.75	
Lubricating oil	2.00	
Anticipated pump repairs, annually	25.00	
Attendance estimated	20.00	
	\$625.75	\$625.75
		\$893.43

Total cost per acre-foot	\$2.18
Total cost per acre-foot-foot	0.040
Operating cost per acre-foot	1.53
Operating cost per acre-foot-foot	0.028
Operating time, approximately	2500 hr

tion pumping is briefly described herewith. More than 50 farmers in Cache Valley, which lies in northern Utah and southern Idaho, obtain water for irrigation by pumping from the Bear River. A valuable feature about the Bear River water supply is the assurance of an adequate quantity of water by the power company that supplies electrical energy for pumping. The power company, by installing a very large pumping plant at the outlet of Bear Lake, uses Bear Lake as a storage reservoir to equalize the river flow for power purposes. After being pumped out of the lake, the stored water is commingled with the natural flow of the Bear River that generates electrical power at three points on the river before it reaches Cache Valley. Pumping water from the river in Cache Valley for irrigation purposes supplies a favorable market for power, and, since the quantity of water pumped by the irrigators is small as compared to the total quantity in the river, the practice of irrigation pumping is encouraged by the power company. This source of water for pumping is economical, satisfactory, and reliable. The pumped water that is not consumed in the production of crops returns to the river and is used to generate power at a plant a few miles downstream from Cache Valley. The major crops produced with the pumped water are alfalfa, sugar beets, and the grain crops, wheat, oats, and barley.

66. Ground Waters Ground waters constitute a very important source of water for irrigation. Pumping from wells for irrigation is

practiced to a considerable extent in the older irrigated countries, notably Egypt and India. Pumping from wells is also practiced to some extent in nearly all the arid states of the West.

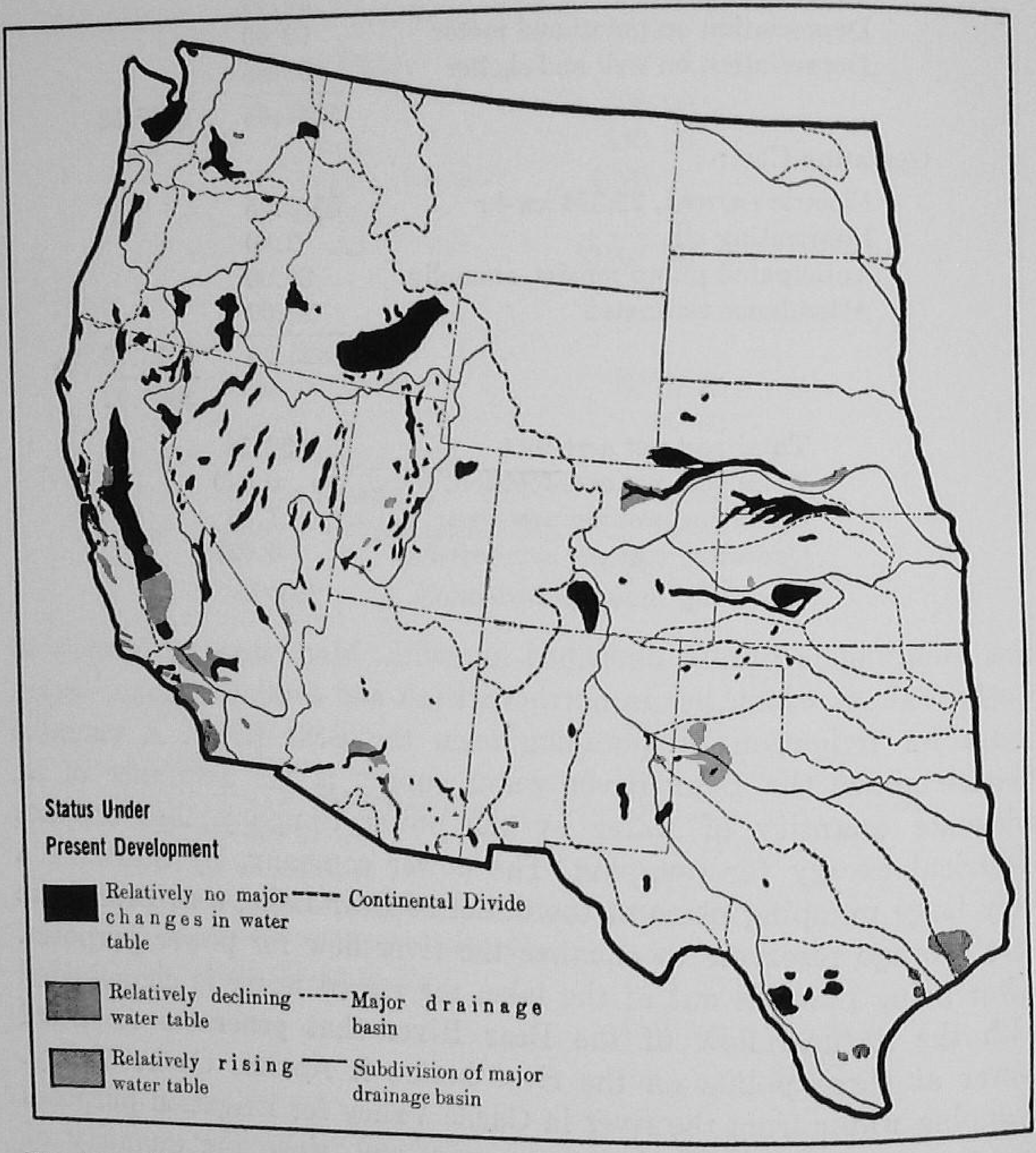


FIG. 57. General ground-water basins in the 17 western states. (*U.S.D.A. Misc. Pub.* 504.)

The locations of ground-water basins in the 17 western states are shown in Fig. 57.

The Office of Land Use Coordination, United States Department of Agriculture, estimated that about 10 percent of the irrigated land in the United States received all its water from ground-water sources and another 10 percent received part of its supply from ground water. In 1920 nearly 35,000 irrigation wells were used; in 1930 the number was 58,000; and in 1940 it was 79,000.

As indicated in Fig. 57, in some of the ground-water basins, up to 1942, the water table declined as the result of pumping; in others there was no major change; and in a few the water table rose during the period of records. It is essential always to avoid overexpansion of irrigated areas that may be followed by serious water shortages during periods of low precipitation. Special caution against overdevelopment is necessary in the use of ground water for irrigation. Undue lowering of the ground-water surface results in higher lifts and sometimes in prohibitive pumping costs. If pumping is excessive when horizontal-shaft pumps that depend on suction lifts are used, it may become necessary to deepen pump pits and lower the pumps in order to obtain sufficient quantities of water.

The extent of irrigation pumping from ground-water supplies should therefore be determined on the basis of thorough, long-time investigations of the quantity of annual inflow or recharge to the ground-water streams, basins, or reservoirs. Individual irrigators as a rule have neither time nor funds essential to such investigations, which must therefore be conducted by public agencies.

Landowners and their engineers can make essential decisions concerning development of ground-water supplies for irrigation after checking "yes" or "no" on twelve important points, listed in the questionnaire.

	Yes	No
A. Availability, quality, and depth of water:		
1. Is a plentiful supply of water available?	☐	☐
2. Is available water of the right quality to permit production of the desired crops?	☐	☐
3. Is water available at a depth that will permit economical pumping?	☐	☐
B. Trend of the water table:		
4. Is the water table stable?	☐	☐
5. Is it rising?	☐	☐
6. Is it declining?	☐	☐
7. Is development in the area likely to bring about withdrawals of water in excess of the natural recharge?	☐	☐
C. Legal or natural protection:		
8. Do the statutes or court decisions provide legal or administrative protection in your area against depletion of water supplies, or	☐	☐
9. Is the area protected against overexpansion and depletion by "natural" controls?	☐	☐
D. Cost of operation:		
10. Will the prospective production under irrigation bring enough		

	Yes	No
returns to pay the increased costs of irrigation farming?	☐	☐

E. Land requirements:

11. Is the land physically suitable for irrigation from the standpoint of contour, productivity, water-holding ability? ☐ ☐
12. Is the land suitable for the types of crops to be produced? ☐ ☐

The feasibility of checking the above points with satisfactory decisions of "yes" or "no" depends on the results of investigations in which the public is vitally interested.

67. Wells and Casing For small quantities of irrigation water, wells are sometimes dug by hand methods and lined either with lumber, concrete, brick, or stone masonry. In general, however, irrigation wells are drilled or bored by mechanical methods, using gasoline engines or other portable power equipment. Rohwer groups the different methods of drilling wells into:

Driven wells	Standard method
Dug wells	California or stovepipe method (mud-scow method)
Large pits	Sand-pump and orange-peel-bucket methods
Bored wells	Hydraulic rotary method
Drilled wells	New hydraulic rotary method

Mechanical methods of well drilling have the advantage of permitting the work to proceed in water, whereas some hand-dug wells require special provision to remove the water from the wells as the digging proceeds. The mechanical methods are especially advantageous where it is essential to make wells of considerable depth in order to get a sufficient quantity of water. A typical driven well with modern drive plant and screen is shown in Fig. 58. Wells of this type are low in first cost. In favorable sand formations they are useful and efficient both for irrigation and for drainage. Drilled irrigation wells as a rule range in diameter from 6 to 40 in. with the largest number 16 to 20 in. These wells are lined with sheet-metal casing, the thickness of which increases as the diameter and depth of the well increases as shown in Table 15. For example, a 16-gage casing having thickness of 0.0625 in. is recommended for 8-in. diameter wells not deeper than 70 ft; whereas 10-gage casing 0.14 in. thick is considered necessary for 36-in.-diameter wells only 20 ft deep if reinforcing boards are not used.

If it is desired to use a horizontal-shaft pump it is essential to dig a

pit of sufficient depth to place the pump on an elevation within suction distance of the water while pumping. A combination of a drilled well together with a pump pit and a centrifugal pump direct-connected to a horizontal-shaft motor used at the University of Arizona is illustrated in Fig. 59. A typical deep well with a turbine pump installed is shown in Fig. 60. The pump bowls are below the water level while pumping. A vertical-shaft motor also direct-connected to the pump is placed above the ground surface. During pumping, water flows through perforations in the casing, commonly made after the well is drilled and the casing is placed. Great care must be exercised to assure adequate perforations of the casing without causing danger of collapse of pipe. As yet there seems to be no definite agreement among engineers as to the ratio of the total cross-section area of perforations to cross-section area of the well casing, although all agree that adequate perforating is essential to guard against excessive loss of mechanical energy as the water flows into the well. An example of perforating before the casing is placed in the well is presented in Fig. 61.

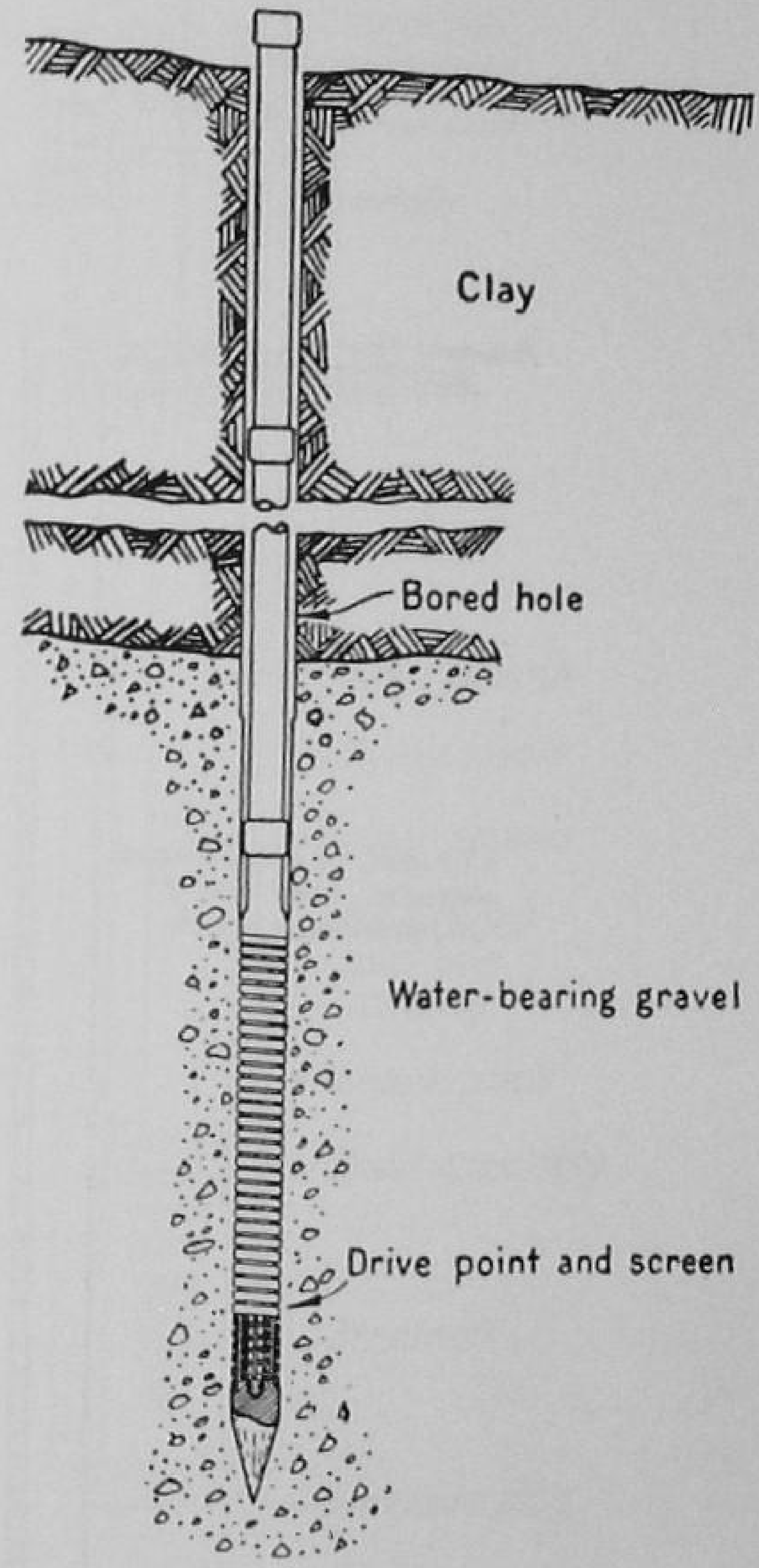


FIG. 58. Cross section of a driven well with modern drive point and screen. (*U.S.D.A. Circ.* 546.)

68. Developing Wells The permeability of soils, sands, and gravels increases rapidly with the increase in diameter of particles, as stated in Chapter 10. It is therefore important that the fine particles outside the well casing be drawn into the well and brought to the surface either by pumping or by means of a sand bucket. The process of removing silts, sand, and very fine gravel so as to facilitate the flow of water into the well is known as "developing the well." Most experienced drillers understand the importance of this work, and some have developed ingenious methods of washing and jetting with water and with com-

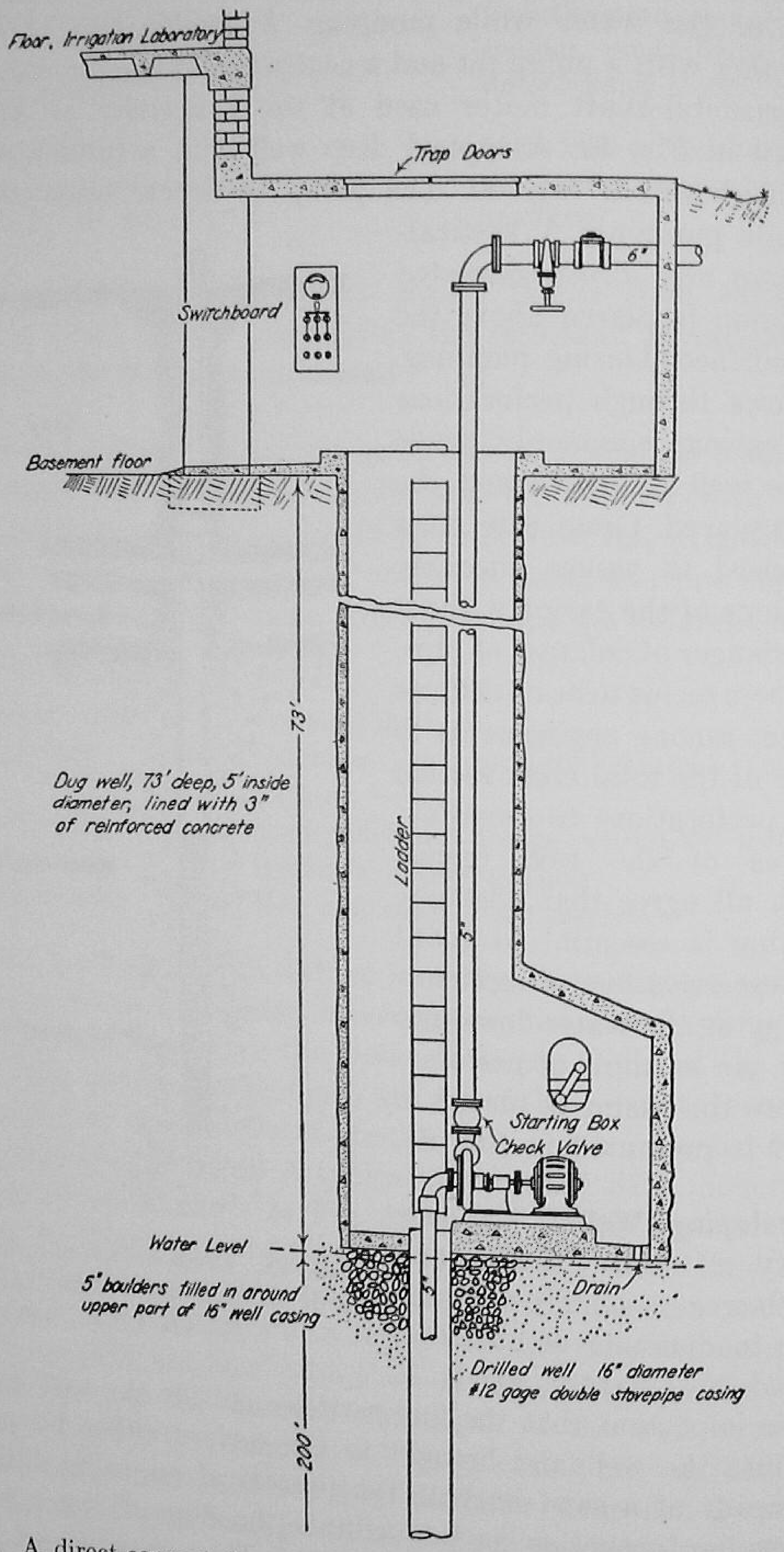


FIG. 59. A direct-connected pumping unit in a combined pit and drilled well. (*Univ. of Arizona Agr. Exp. Sta. Bul.* 99.)

pressed air in order to accomplish this result. One method is to plunge a sand bucket up and down near the perforation, thus drawing water into the well; another is to vary the discharge of the pump and

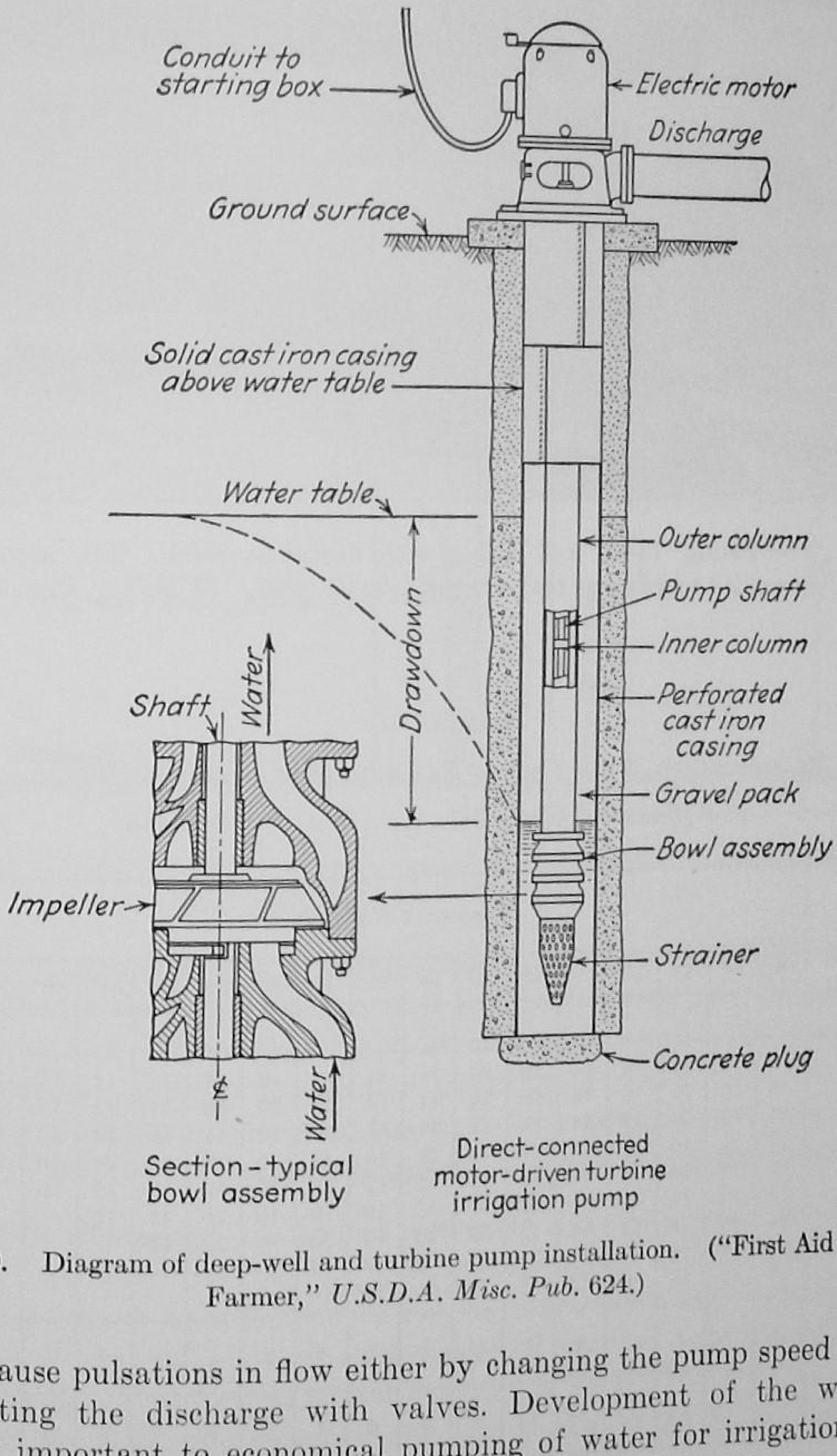


FIG. 60. Diagram of deep-well and turbine pump installation. ("First Aid for the Farmer," *U.S.D.A. Misc. Pub.* 624.)

thus cause pulsations in flow either by changing the pump speed or by regulating the discharge with valves. Development of the well is highly important to economical pumping of water for irrigation and should never be neglected. Sometimes the yield of a well at a given drawdown may be doubled or trebled by proper developing.

FIG. 61. Perforating 14-in. well casing with acetylene torch. The sections of casing are welded together as they are put into the well. (*U.S.D.A. Circ.* 546.)

TABLE 15

RECOMMENDED WELL CASING THICKNESS FOR SHALLOW WELLS

U. S. Standard Gage (*Colo. Agr. Exp. Sta. Bul.* 415)

Depth of Well	Diameter of Well Casing, in.																
	8	10	12	14	16	18	20	24	26	30	36	42*	48*	54*	60*	66*	72*
Ft																	
20	16	16	16	16	16	16	14	14	14	12	10	16	16	14	12	12	10
30	16	16	16	16	16	14	14	14	14	12	10	16	14	12	12	10	10
40	16	16	16	16	14	14	14	14	12	12	10	14	14	12	10	10	10
50	16	16	16	14	14	14	14	12	12	12	10	14	14	12	10	10	10
60	16	16	14	14	14	14	14	12	12	10	10	12	12	10	10		
70	16	14	14	14	14	14	12	12	10	10	10	12	12	10			
80	14	14	14	14	14	12	12	10	10	10	10	12	12				
90	14	14	14	14	12	12	12	10	10	10	10	12					
100	14	14	14	14	12	12	10	10	10	10	10						
Band thickness,† in.	¼	¼	⅜	⅜	⅜	⅜	⅜	⅜	⅜	⅜	⅜	½	½	½	½	½	½
Band width,† in.	1	1	1½	1½	1½	1½	2	3	3	3	3	3	3	4	5	5	5

* Reinforcing bands placed on inside of casing at 3-ft intervals and on the outside at top and bottom.

† Thickness and width of top and bottom reinforcing bands and intermediate bands for casing over 42 in. in diameter. Gage thickness of casing to be the same for the entire depth of well.

69. Water Yield of Wells The size of stream of water obtained for irrigation from a well with a pumping plant is determined by one or both of two major factors, namely: (*a*) the capacity of the pump and the horsepower of the motor or engine; and (*b*) the capacity of the well, which depends on the slope of the drawdown curve of the water surface, or pressures, the depth and effective diameter of the well, and the permeability of the water-bearing material. Pump

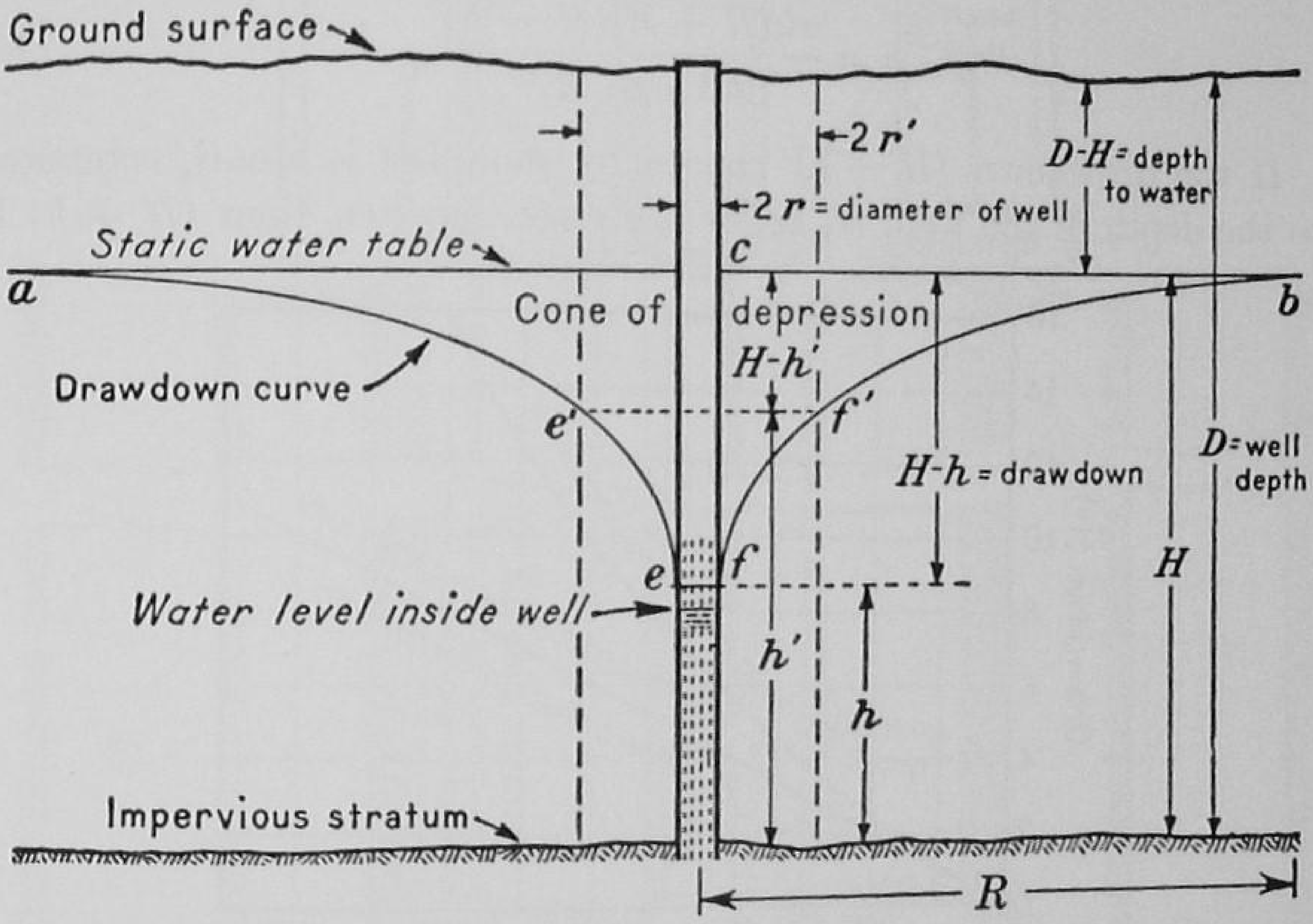


FIG. 62. Vertical cross section of a typical irrigation well in a non-artesian formation. (Not to scale.) (*U.S.D.A. Circ.* 546.)

capacities and horsepower requirements to lift given quantities of water through specified heights are well understood and may be predicted within fair precision. It is far more difficult to predict the horsepower requirement to drive a specified quantity of water from the water-bearing sands or gravels into the well, because this involves uncertain permeability of the sands and gravels through which the water flows.

70. Well Discharge A typical section in a vertical plane through the axis of an irrigation well in free or unconfined ground water (non-artesian water) is presented in Fig. 62. For steady flow into the well, $q = av$. Select, for example, a cylinder of vertical axis having radius r' and height h'. The area of this cylinder is $2\pi r'h'$. The velocity of flow toward the well, according to the Darcy law, when k is the permeability, is

$$v = k\frac{dh}{dr}$$

and therefore the quantity of radial flow toward the well is

$$q = av = 2\pi r'h'k\frac{dh}{dr}$$

Separating the variables and integrating this differential equation between the limits of r and R in the horizontal plane and h and H in the vertical plane, the result is:

$$q = \frac{\pi k(H + h)(H - h)}{2.3 \log_{10} R/r} \qquad (26)$$

If the drawdown $(H - h)$ caused by pumping is small, compared to the depth of the well, H, below the water surface, then $(H + h)$ is

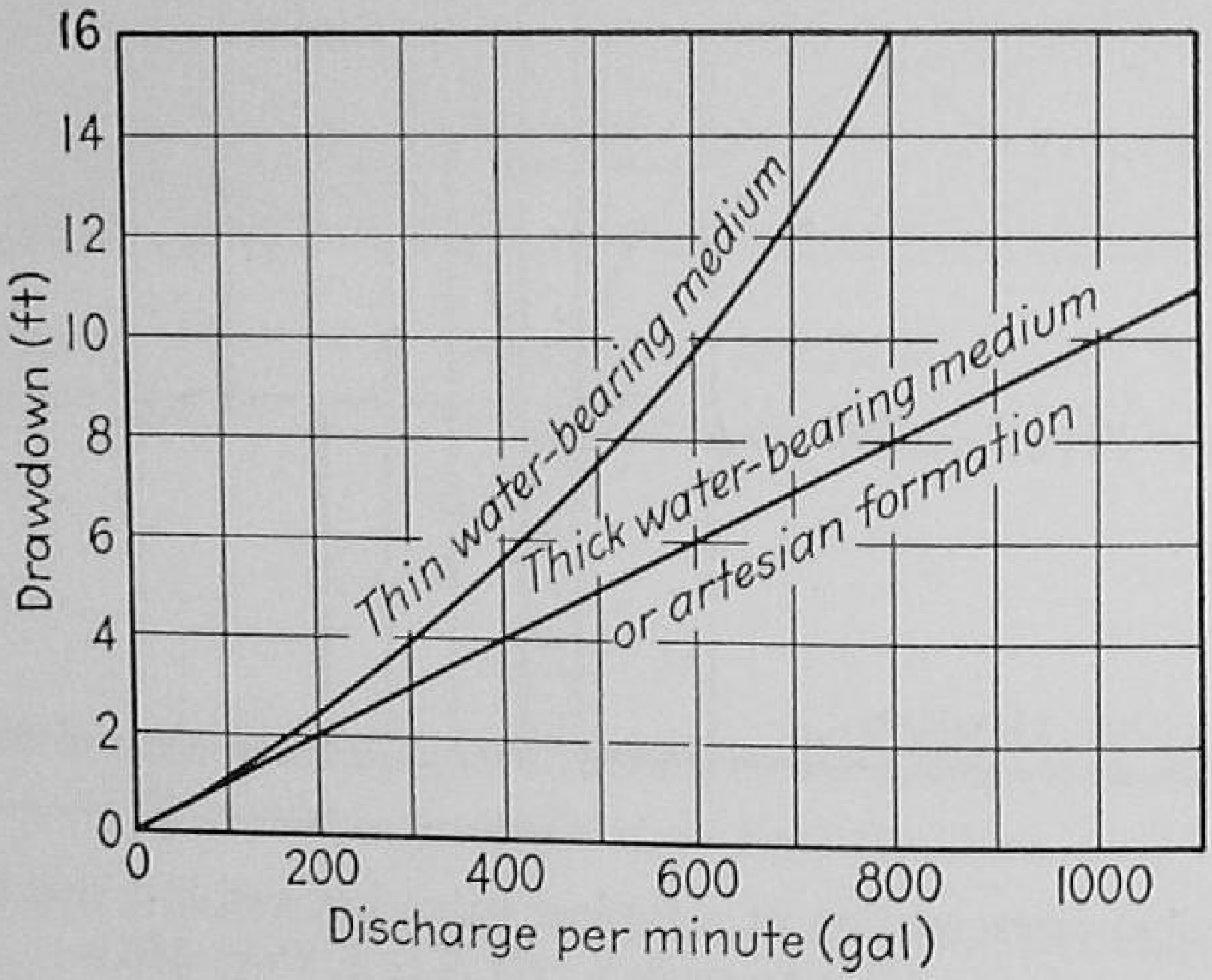


FIG. 63. Typical discharge drawdown relation of a well in a thin water-bearing formation and one in a thick water-bearing formation or an artesian stratum. (*U.S.D.A. Circ.* 678.)

equal approximately to $2H$. For these conditions, two important and fundamental facts are shown by equation 26:

1. That, for any given drawdown and permeability, the quantity of flow is *substantially* directly proportional to the effective depth of the well or the depth, H, below the static ground-water surface.

2. That increasing the diameter of the well $(2r)$ has much less effect because the quantity varies with the logarithm of the diameter.

To illustrate the significance of these important facts, doubling the *effective* depth, H, of a 6-in. well will double its discharge, provided there is no interference from other nearby wells, whereas doubling its diameter will increase the discharge only 10 percent and increasing the diameter 4 times will increase the discharge less than one-fourth.

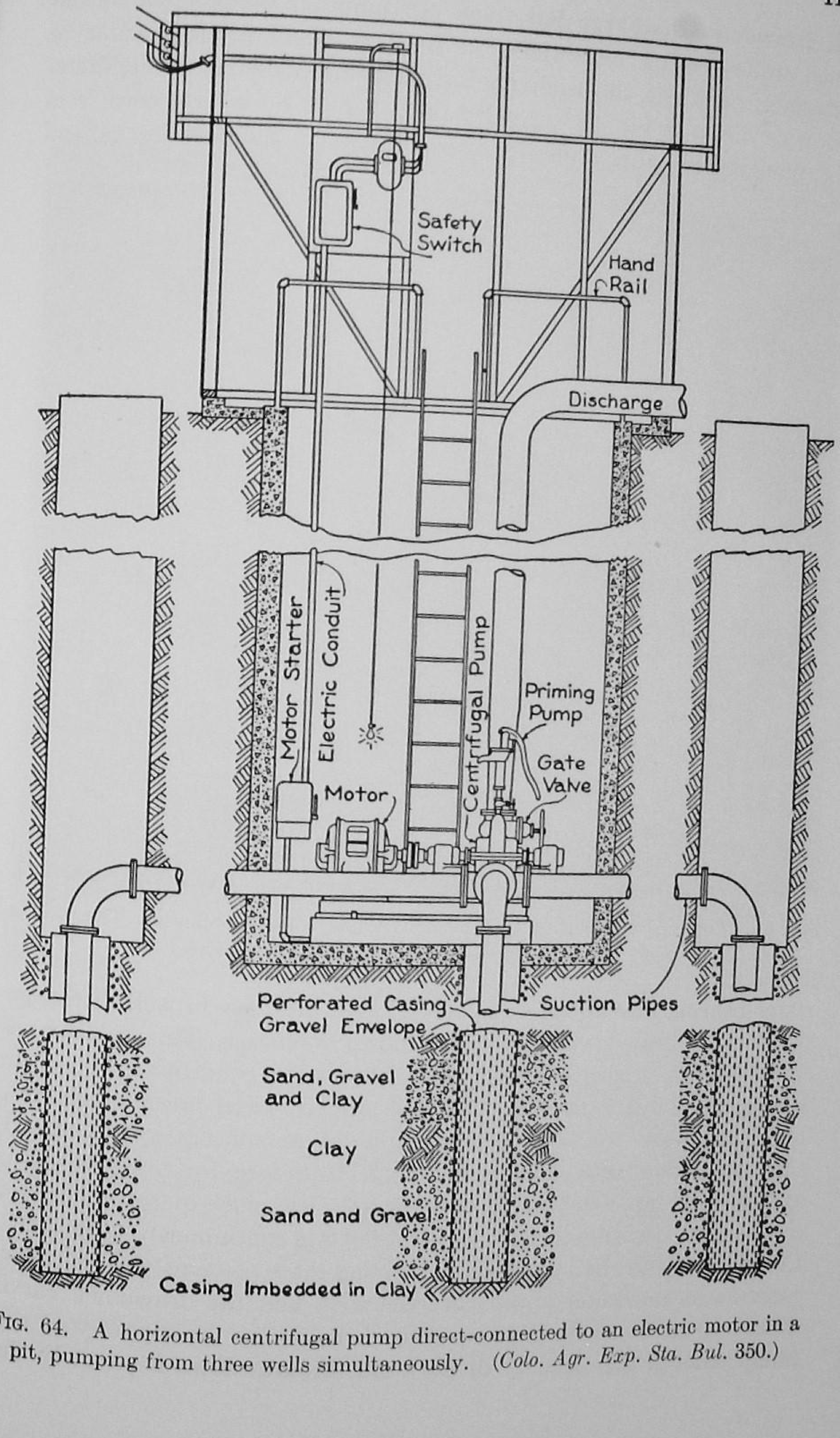


FIG. 64. A horizontal centrifugal pump direct-connected to an electric motor in a pit, pumping from three wells simultaneously. (*Colo. Agr. Exp. Sta. Bul.* 350.)

71. Drawdown-Discharge Relations In pumping from thick unconfined water-bearing formations, or from confined ground water or artesian formations, the discharge is directly proportional to the drawdown as shown in Fig. 63, provided that there is no interference from the pumping of other wells in close proximity. Shallow unconfined

FIG. 65. Pumping installation in the San Ramon walnut orchard. The well is 554 ft deep. (Courtesy Soil Conservation Service.)

water-bearing formations sustain a gradual decrease in well discharge per foot of drawdown as the drawdown increases. This relation is shown in the upper curve of Fig. 63. Under conditions of rather homogeneous water-bearing sands and gravels, water flows, in general, radially toward the well through a series of concentric cylindrical surfaces having the well as vertical axis. Therefore, for constant yield, as the water approaches the well its velocity must increase because the cross-section area through which it flows is continuously decreasing. Consequently the hydraulic slope (driving force per unit weight) must increase as the water approaches the well, and the drawdown curve becomes steeper as the well is approached. Where the capacity of the pump exceeds the capacity of the well, the drawdown is excessive in

the immediate vicinity of the well. It is therefore desirable, if practical, to provide a large "effective" diameter of well to avoid excessive drawdown (and power requirements) in order to drive the water into the well.

Fig. 66. A pump installation where the water is pumped 2 ft higher than need be. The stilling basin with three baffles is very effective. (Courtesy Soil Conservation Service.)

72. Battery of Wells In places where the water-bearing materials have low permeability it is sometimes advantageous to draw water with one pump from two or more wells. This practice is illustrated in Fig. 64, in which one horizontal-shaft pump draws water from three wells at the same time. The most economical spacing of wells, where two or more are constructed to supply one pump, is a problem to be given thorough scientific study. Wells should be far enough apart to reduce interference to the minimum.

73. Typical Irrigation Wells A modern electric-driven pump is illustrated in Fig. 65. From this well water may be pumped direct to

the ditch near the well when the gate valve is open as indicated in the figure. When the operator closes the gate valve water is conveyed from the pump through a concrete pipe line 4300 ft long to the upper end of the orchard.

A typical pumping plant is illustrated in Fig. 66, which shows that water is pumped 2 ft higher than necessary. To save power costs it is important to deliver the water to the surface of the land and no higher. Figure 66 illustrates typical baffles to reduce velocity of the pump water before it is delivered to the unlined distributing ditch on the farm.

6
Irrigation Methods

Irrigation water is applied to land in four general methods, namely: (*a*) flooding the surface; (*b*) in furrows, thus wetting only part of the ground surface; (*c*) sub-irrigation, in which the surface is wetted little if any; and (*d*) sprinkling, in which the soil surface is wetted much as it is by rainfall.

These methods are further subdivided as indicated below and as considered in the following articles.

(*a*) Flooding:
1. From field ditches.
2. Border.
3. Check.
4. Basin.

(*b*) Furrow:
5. Large deep furrows for such cultivated crops as potatoes, corn, and asparagus, and for orchards.
6. Corrugations or small shallow furrows for grains, alfalfa, and sugar beets.

(*c*) Sub-Irrigation:
7. Controlled by lateral supply ditches.
8. Uncontrolled by excess application of water to higher lands.

(*d*) Sprinkling:
9. Pipe distribution system.
10. Circular system.

Irrigation methods vary in different parts of the country and on different farms within a community because of differences in soil, topography, water supply, crops, and customs. Forage crops such as alfalfa, clover, hay, and pastures in some areas are irrigated by use of corrugations. Flooding methods of irrigation are suitable for forage crops, border strips, contour ditches, and basins. Row crops are irrigated by furrows and borders. Any one or a combination of several methods may be best suited to one farm, as illustrated in Fig. 67.

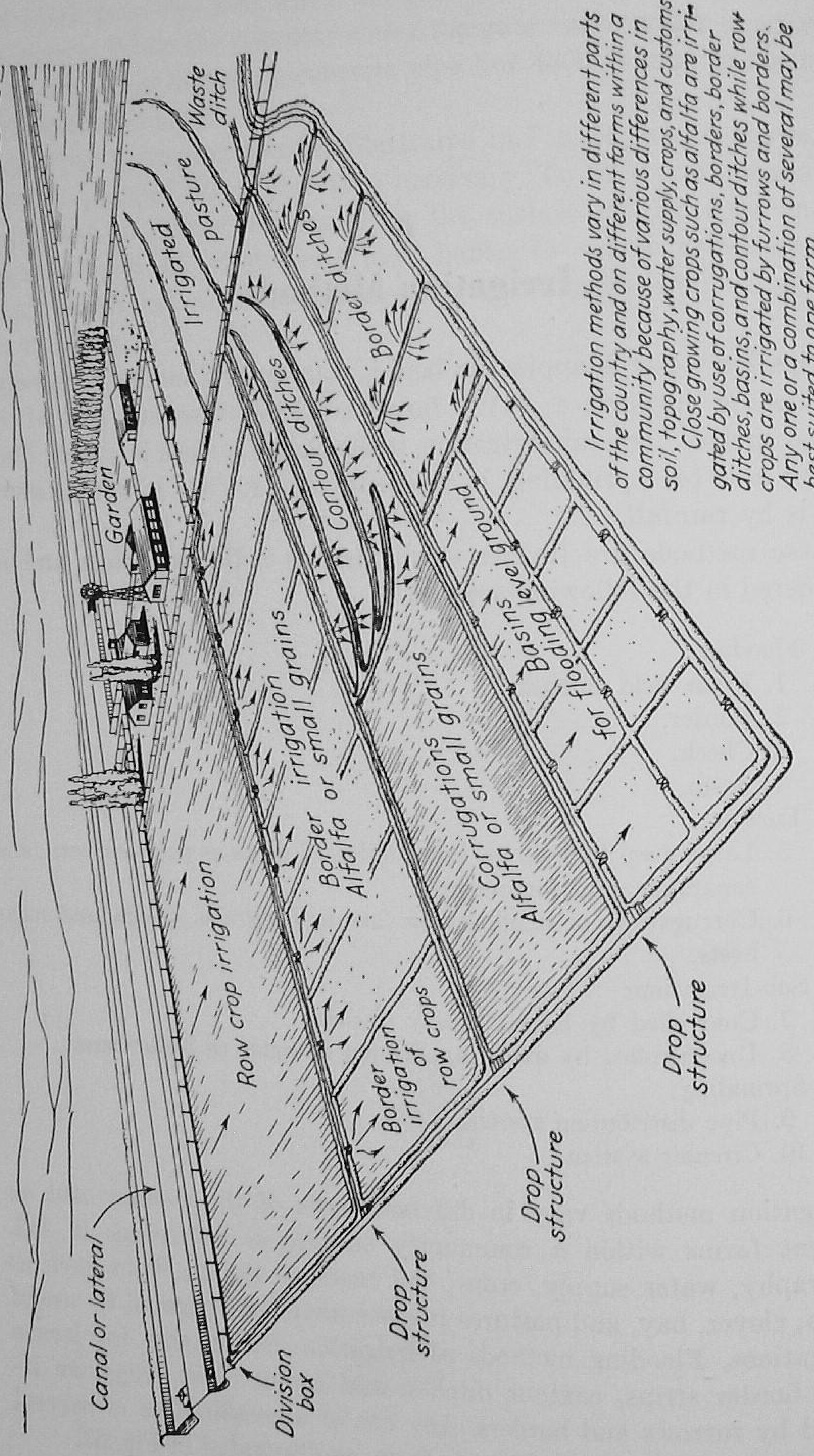


FIG. 67. Various methods of applying irrigation water to field crops. (Farm Security Adm.)

74. Primitive and Modern Flooding In the early irrigation of centuries past, throughout Asia and southern Europe, water was applied by flooding extensive areas of rather smooth, flat land. In Egypt, especially, the flooding method was of general adoption, the water being forced to spread over vast tracts, during the season of high stream flow.

In modern American irrigation, several improved flooding methods have been developed. Brief descriptions of these methods are given in the following paragraphs.

75. Ordinary Flooding from Field Ditches Where water is applied from field ditches without any levees to guide its flow, or otherwise restrict its movement, the method is designated *ordinary flooding*. It is practiced largely in the Rocky Mountain states, particularly in the places where irrigation water is abundant and inexpensive.

In some flooding methods, the storage capacity of the soil for available soil moisture should be satisfied by water percolating into the upper few feet of soil during the time it is flowing over the land surface. If the water is made to flow over too quickly, an insufficient amount will percolate into the soil. On the other hand, if it is kept on the surface too long, waste will result from percolation into the deep subsoil, gravels, or water table. It is an important and difficult problem to balance the application of water in the flooding methods so as to attain a high efficiency in its application. The size of stream used, the depth of water as it flows over the surface, and the rate of infiltration of the water into the soil; all influence this balance in the application of water, as is shown more fully in Articles 77 and 78.

In ordinary flooding, much depends on the smoothness of the land surface, the proper size of irrigation stream, and the attention and skill of the irrigator, but it is difficult with this method to attain high efficiency in irrigation. The water is brought to the field in permanent supply ditches and distributed from ditches built across the field spaced from 50 to 150 ft apart, depending on the grade of the land, the texture and depth of the soil, the size of stream, and the nature of the crop. The distances between the diversions from ditches down the steepest slope are similarly determined.

Flooding from field ditches is well adapted to some lands that have such irregular surfaces that the other flooding methods are impossible. However, even on lands that may advantageously be irrigated by the other flooding methods, irrigators continue to use the ordinary one because of the low initial cost of preparation of land for this method. The extra labor cost in the application of water and the

greater losses of water by surface runoff and deep percolation usually offset the apparent advantages of low initial cost of preparation of land.

Where land, water, or labor is expensive, where soil is deep and not likely to crust badly, and where the land is not too rough or steep, it is generally advisable to prepare for controlled flooding in border strips or level or contour basins.

76. Border-Strip Flooding Dividing the farm into a number of strips, preferably not over 30 to 60 ft wide and 330 to 1320 ft long, separated by low levees or borders, is designated the *border-strip method.* Water is turned from the supply ditch into these strips along which it flows slowly toward the lower end, wetting the soil as it advances.

Figure 68*A* shows the farm lot 74 of the California State Durham Colony before it was prepared for irrigation. The contours indicate that the highest land is on the north border in the west half of the tract. In preparing the tract for irrigation by the border-strip method the agricultural engineers divided it into three fields as shown in Fig. 68*B*. The border strips in each field are 40 ft wide. In the west fields they are 470 ft long; and in the east field, because of the irregular position of the storm channels, the border strips vary in length from a minimum of approximately 150 ft to a maximum of nearly 500 ft. While irrigating the west two fields, the water flows from north to south, and in the east field it flows in two directions, as indicated by the position of the borders and the pointing of the small arrows.

The surface is essentially level between levees, so that the advancing sheet of water covers the entire width of land strip; but lengthwise of the levee the surface slopes somewhat according to the natural slope of the land. It is desirable, although not urgently essential, that the slope be uniform within each levee. If practicable, it is best to make the border slope from 2 to 4 ft per 1000 ft; but slopes as low as 1 ft per 1000 and as high as 75 ft per 1000 may be used where it is impracticable to obtain the more appropriate slopes. Special care is essential to prevent erosion of soil on the higher slopes.

The size of stream turned into a single border varies from ½ to 10 cfs, depending on the kind of soil, the size of border, and the nature of the crop.

Because of the relatively high initial cost of preparing land for the border method, it is desirable to plan the location of the levees and strips so that different forage and grain crops may be irrigated with the same borders. Crops which are to be furrow-irrigated, such as

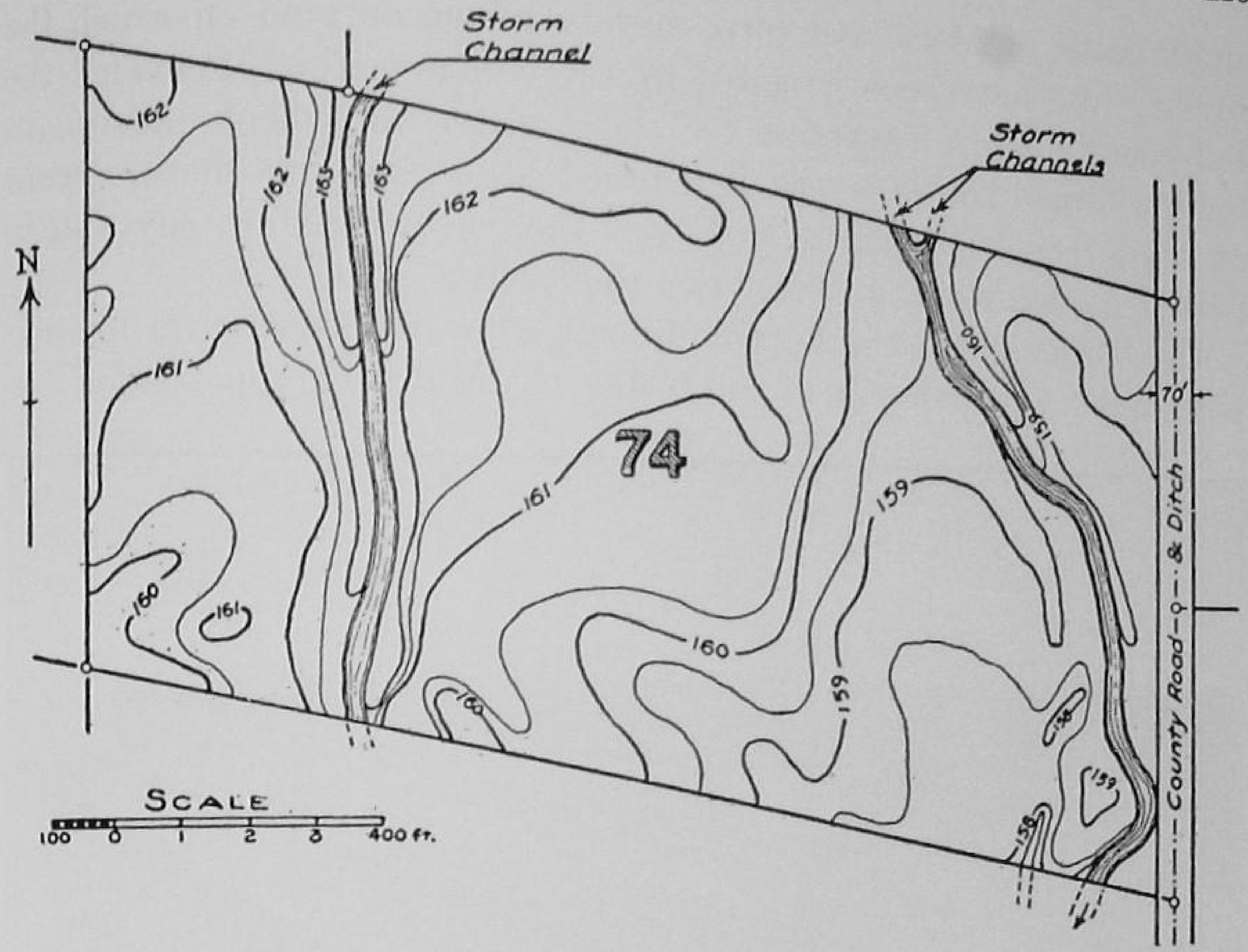


FIG. 68*A*. Farm lot enlarged, showing contours. (*U.S.D.A. Farmers' Bul.* 1243.)

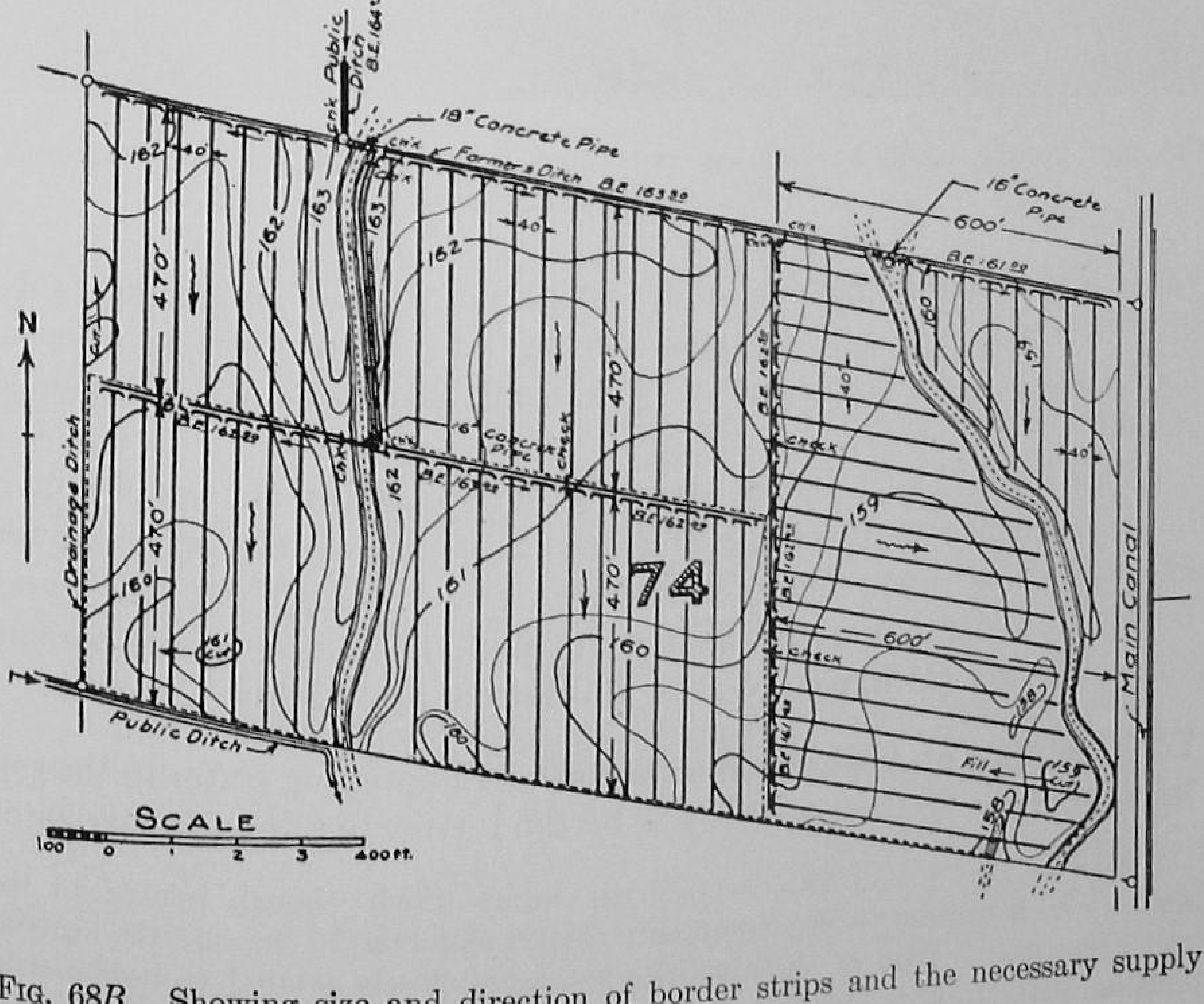


FIG. 68*B*. Showing size and direction of border strips and the necessary supply ditches and draws.

sugar beets, potatoes, and corn, may be grown on land on which the forage crops have been irrigated by the border method. Provided the soil conditions are favorable to lateral water movement underneath the low, broad border levees, it is practical to plant and mature crops on the levees. It is difficult to furrow the levees satisfactorily and to keep irrigation water in furrows on the levees.

The border method is suitable to soils of wide variation in texture. It is important, however, to study the physical soil properties in ad-

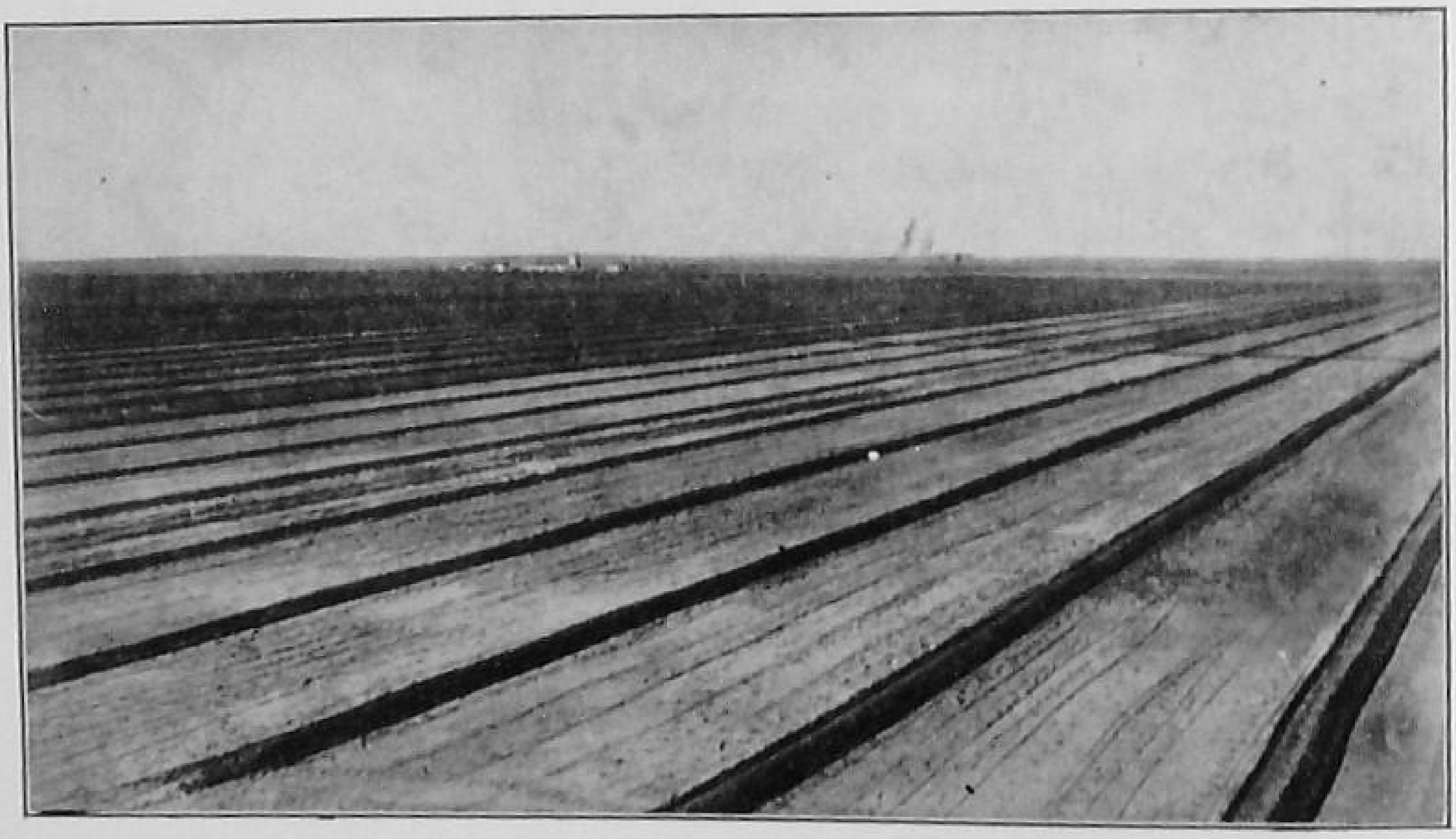


FIG. 69. Newly made borders on the Hoover farm near Wasco, California. (*U.S.D.A. Farmers' Bul.* 1243.)

vance of preparing land for border irrigation. Rather impervious subsoils overlain by compact loams permit long border strips, whereas open soils having porous, gravelly subsoils necessitate short narrow strips.

At the head of each border strip a gate is placed in the supply ditch for convenience in turning water into and out of the strip. Power machinery and equipment for smoothing and completing the levees for border irrigation are illustrated in Chapter 7. Newly made borders on the Hoover farm, near Wasco, California, are shown in Fig. 69.

77. Time Rate of Application of Water* In applying water to the soil by most of the flooding methods or by the furrow methods, the irrigator

* Articles 77, 78, and 79 concern basic topics which, though related to the methods of irrigation, are not commonly classed as methods. Because the analysis and experimental data of these articles are more closely related to border-strip flooding than to other methods, they are presented here.

endeavors to cause enough water to percolate into the soil to moisten it fully to the depth of the root zone during the time that the sheet of water is flowing over the land surface. Ponding water on the land in order to assure its adequate percolation into the soil is generally impracticable in connection with either the flooding or the furrow methods. It is therefore desirable that size of irrigation stream applied to unit area of land be varied according to the rate of infiltration of water into the soil.

When a large stream is applied to a unit area of soil of low infiltration rate, excessive surface runoff occurs, whereas, when a small stream is applied to a unit area of soil of high infiltration rate, excessive depths of water are lost through deep percolation. The relation between size of stream, area of land irrigated with a given stream, and the time rate of water application can be most easily stated by means of a rational equation.

Let A_r = area in acres irrigated in a single run without turning the stream, i.e., in a border strip or a check.

q = the quantity of water in cubic feet per second or acre-inches per hour turned into a single strip or check.

R = time rate of application in cubic feet per second per acre based on the area irrigated in a single run, A_r.

The time rate of application is defined as the ratio of q to A_r, i.e.,

$$R = q/A_r \tag{27}$$

A study of the relation of R to the average depth, d, required to cover all the surface of a 1-acre border strip in Sacramento Valley, California, having a slope of 3 ft per 1000 ft, shows that, as the time rate increases, the required depth decreases. The results of the experiment are as follows:

Rate of Application R	Depth of Water Required, Inches d
4.6	33.0
10.1	22.3
13.5	13.9
15.3	10.1
17.8	8.3

78. Analysis of Time to Cover a Given Area with Water Consider a border strip or other tract irrigated by flooding a thin sheet of water over the land. The water advances most rapidly immediately after

being turned onto the land. Soon thereafter, part of the stream is disposed of by percolating into the soil, so that the quantity of water flowing on to dry land gradually decreases. If the size of irrigation stream, the average depth of the overflowing sheet, and the rate of infiltration are known, and if they are fairly constant, it is possible to compute the approximate time required to cover a given area.

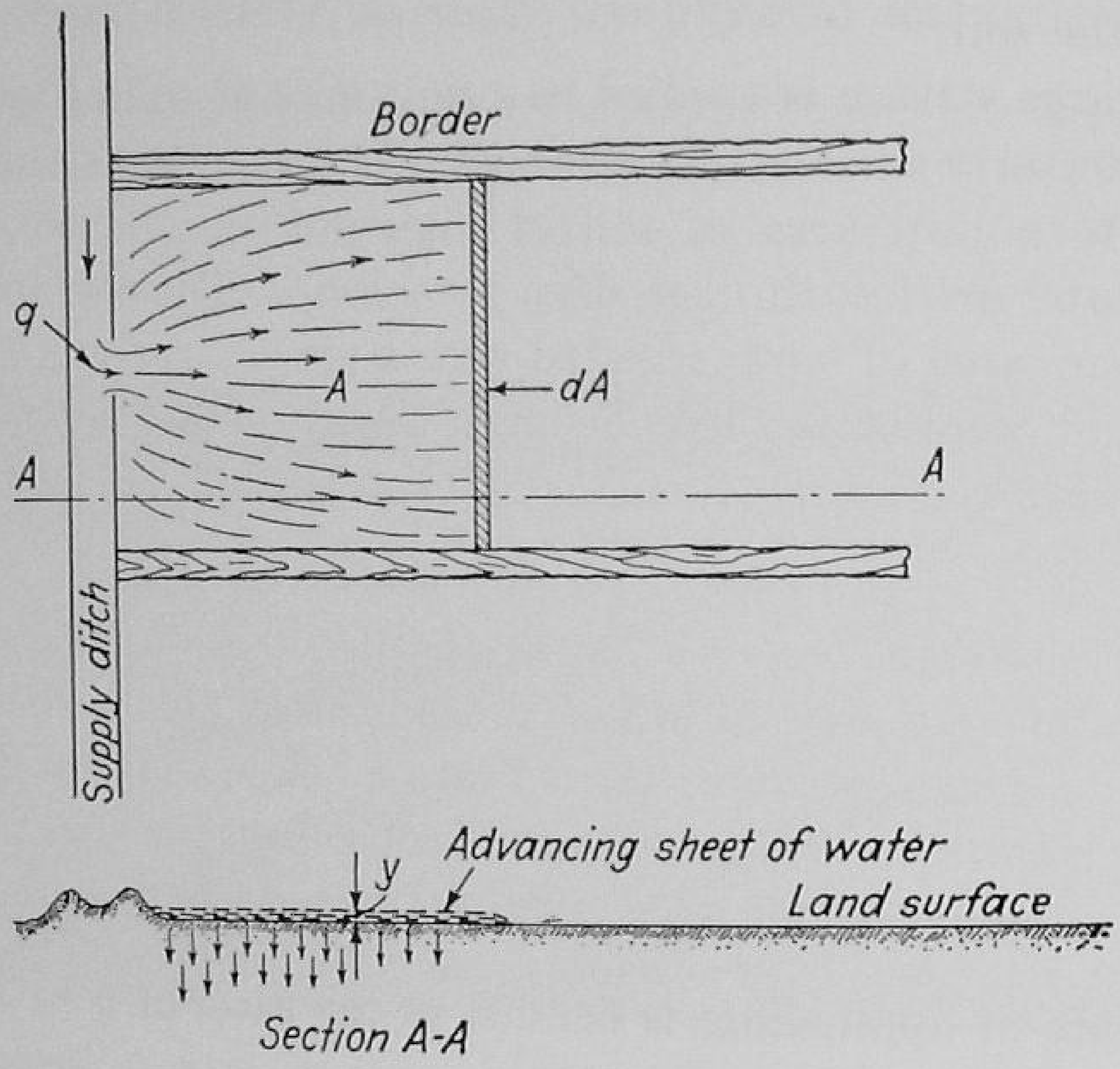


FIG. 70. Illustrating irrigation water being applied to a border strip, and how the water moves forward to cover a very small area, dA, in a short time, dt, and also how it percolates into the soil of the upper part of the strip.

The student who is familiar with calculus will understand the analysis. Other students, for the present, will find the resulting equation 28 of interest without checking fully the reasoning leading to its development.

Let A = area covered with water at any time, t, after the water was turned on the land, as illustrated in Fig. 70, acres.

I = rate of infiltration of water into the soil of the wetted area, surface inches per hour.

q = quantity of water turned on to the strip, acre-inches per hour (cubic feet per second).

t = time after the water was turned onto the land, hours.

y = average depth of water as it flows over the land, inches.

The volume of water that flows into a border strip or onto the

land in any given short time, say 1 min, is disposed of in two ways:

1. Part flows down the strip and covers more land.
2. Part percolates into the soil.

The volume that flows into the strip in a time dt seconds is $q\,dt$. The volume that flows past any given point to wet more land is $y\,dA$. The volume that percolates into the soil in time dt is $IA\,dt$. Therefore, since in the differential time dt the water advances over the area dA and also percolates into the soil of the area A, at a rate I, it follows that

$$q\,dt = y\,dA + IA\,dt$$

and

$$dt = \frac{y\,dA}{q - IA}$$

Integrating, solving for and eliminating the constant of integration, and converting from the natural logarithms to the common system of logarithms, there results, provided y and I are considered constant:

$$t = 2.303\,\frac{y}{I}\log\frac{q}{q - IA} \tag{28}$$

The infiltration rate I is not rigidly constant. It varies somewhat from time to time at a given place; and at a given time it varies from place to place in the field. Also I may vary slightly owing to change in the depth y; but the variation due to this cause is probably of no significance. To illustrate the use of equation 28, assuming that I and y are constant, let

$$A = 0.5 \text{ acre}; \quad I = 2.0 \text{ in./hr}; \quad q = 1.5 \text{ cfs}; \quad y = 2.5 \text{ in.}$$

Then

$$t = 2.303 \times 2.5/2.0 \times \log 1.5/(1.5 - 2.0 \times 0.5) = 1.37 \text{ hr}$$

If the area were increased to 0.7 acre, all other factors remaining constant, it would require nearly 3.4 hr to cover the strip, during which an average depth of 7.2 in. of water would be applied. For an area greater than 0.7 acre, the time and depth requirements increase rapidly, and the maximum area that could be covered, under conditions as given above, is 0.75 acre.

A direct determination of the area of land that may be wetted with a given stream in any time period is preferred by some irrigation authorities. For the longer time periods, direct computation of area has some advantage, and the procedure is therefore presented.

Solving equation 28 for the area A may simplify its use. For example, let

$$x = \frac{It}{2.303y}$$

then

$$A = \frac{[10^x - 1]q}{10^x I} \tag{29}$$

Let

$$q = 2.28 \text{ cfs} \qquad t = 2 \text{ hr}$$
$$I = 4.00 \text{ in./hr} \qquad y = 2 \text{ in.}$$

then

$$x = \frac{4.0 \times 2}{2.3 \times 2} = 1.739$$

and

$$A = \left[\frac{10^{1.739} - 1}{10^{1.739}}\right] \times \frac{2.28}{4.00} = \frac{54.8 - 1}{54.8} \times \frac{2.28}{4.00} = 0.55 \text{ acre}$$

If the minus one in the numerator of the above value of A were disregarded then

$$A = \frac{q}{I} = \frac{2.28}{4.00} = 0.57 \text{ acre}$$

which is only 0.02 acre, or less than 4 percent increase. The depth of flowing water, y, is the most nearly constant of the elements that influence the value of the exponent x. Therefore, as the product $I \times t$ increases and x becomes larger, the condition of infiltration of the entire stream into the wetted area is approached and only a small error is introduced by writing equation 29 in the simpler and ultimate form, i.e.,

$$A = \frac{q}{I} \tag{29a}$$

There are as yet not enough experimental data with which to determine the rate and extent of variation of I and y with time. These variables have been carefully studied by Lewis and Milne. Their report entitled *Analysis of Border Irrigation*, published in 1938, has many equations and figures of interest to advanced and technical students. Figure 71, taken from their report, shows the computed relation between the time and the distance for a variable depth and infiltration rate and also for a constant depth and rate.

Until further data are obtained similar to those of Lewis and Milne, equations 28, 29, and 29a are valuable only as indicating the trend of change in time required to cover different areas. For accurate results, the quantities I and y, which are considered constant in the differential equation, should be treated as variables and carefully measured.

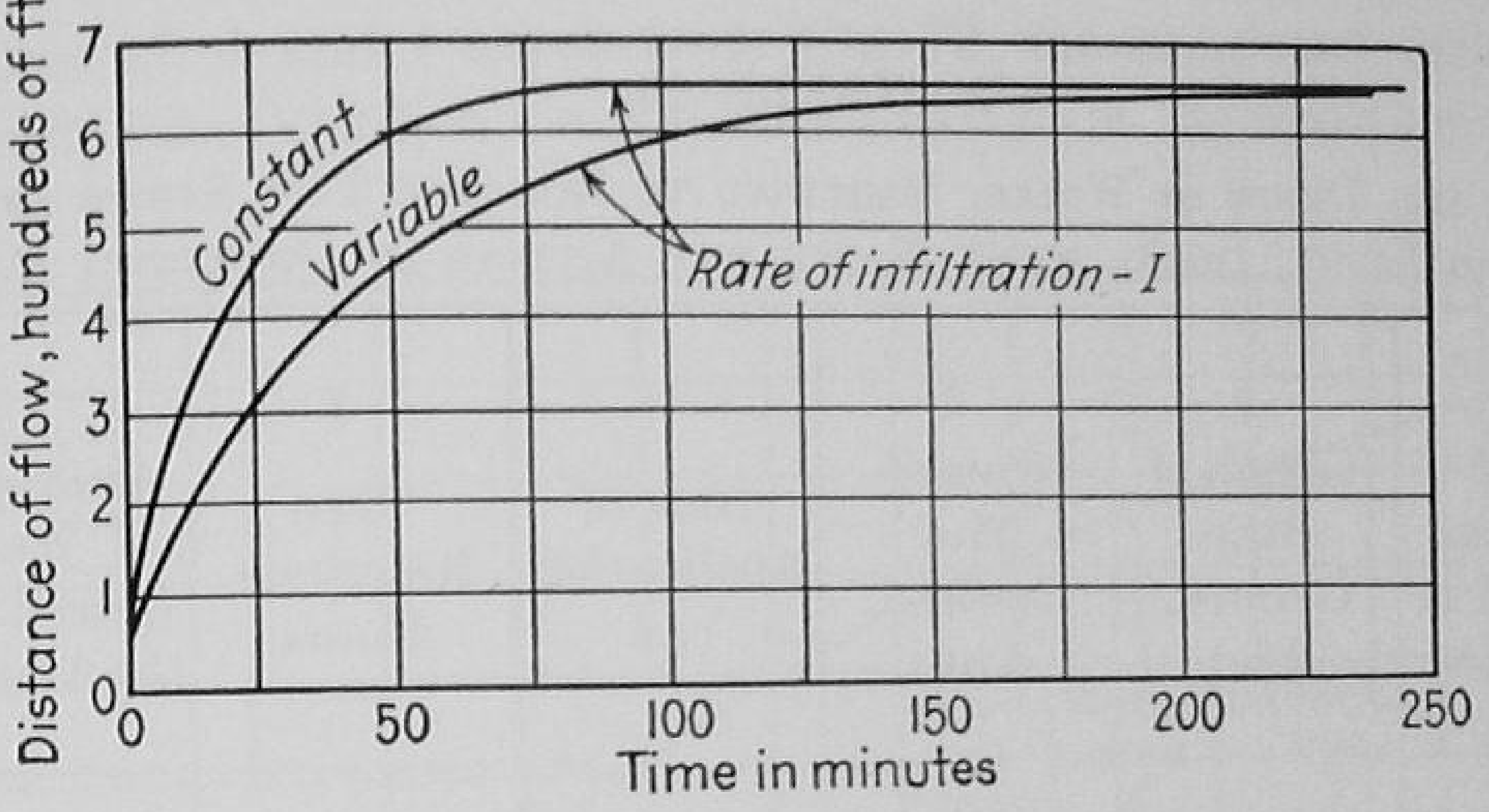


FIG. 71. Relation between time and distance of flow for variable infiltration rate and for constant rate. (*Agric. Eng.*, Vol. 19, p. 270.)

79. Experiments on Time to Cover Different Areas with Water Field experiments have been conducted in the Snake River Valley, Idaho. In the first experiment a border strip of clover land 49.5 ft wide and 2359 ft long was divided into 7 sections, each 337 ft long, containing 0.383 acre. A stream of 2.28 cfs was turned into the strip at the upper end and allowed to flow 23.7 hr as shown in Table 16 in order to cover the entire area of the strip, 2.68 acres. Column 2 shows the length of strip covered and column 3 the area of land covered by the 2.28 cfs stream during the respective time periods given in column 5. Column 4 shows that the time rate of application decreased from 5.8 to 0.8, as the area was increased from 0.383 to 2.684 acres; and column 6 shows that the decreases in rate necessitated an increase in mean depth of irrigation from 8.1 to 20.2 in. The results given in Table 16 suggest that a time rate of application higher than 5.8 would have been better suited to the conditions because 8 in. is rather a large single irrigation. Doubtless three-fourths or more of the 20.2-in. irrigation was lost through deep percolation.

The second experiment reported by Bark was conducted on an alfalfa border strip also near Rigby, Idaho. The strip was 92 ft wide and 2566 ft long. It was divided into 7 plats, each nearly 327 ft long, and a shorter plat approximately 280 ft long, at the lower end. A continuous stream of approximately 7 cfs was run into the strip until

it was completely irrigated. The results of the experiments are presented in part *b* of Table 16.

Had this long strip been divided into 3 strips, each 855 ft in length, by making 2 additional cross ditches, it could have been amply irrigated in much less time. The 7.4-in. irrigation applied to the upper division was doubtless a liberal depth.

TABLE 16

TIME, AND DEPTH OF WATER, REQUIRED TO IRRIGATE TWO STRIPS OF LAND NEAR RIGBY, IDAHO, WHEN WATER WAS APPLIED AT DIFFERENT RATES

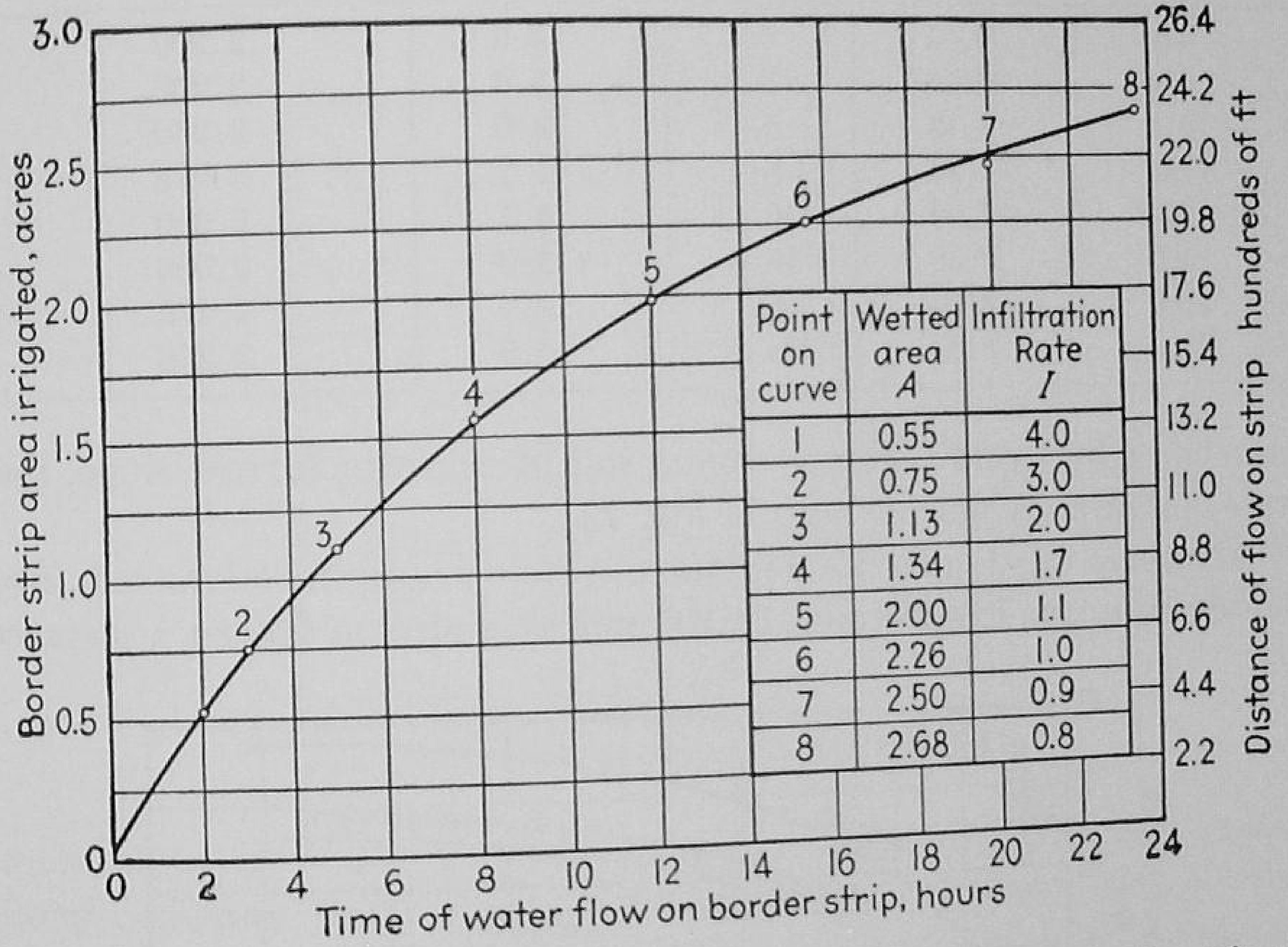
1 No. of Divisions Covered in One Run	2 Length of Strip Covered, Feet	3 Area of Plot Covered, Acres	4 Rate of Application q/A	5 Time Required, Hours	6 Average Depth of Water Required to Cover the Area, Inches
(*a*) *Clover Tract:*					
1	337	0.383	5.8	1.37	8.1
2	674	0.767	2.9	3.20	9.5
3	1011	1.150	1.9	5.20	10.3
4	1348	1.534	1.5	7.70	11.4
5	1685	1.917	1.2	10.70	12.7
6	2020	2.300	1.0	16.70	16.5
7	2359	2.684	0.8	23.70	20.2
(*b*) *Alfalfa Tract:*					
1	327	0.70	10.0	0.75	7.4
2	654	1.41	5.0	1.66	8.2
3	980	2.13	3.3	2.83	9.2
4	1307	2.88	2.4	4.25	10.2
5	1634	3.63	1.9	6.25	11.9
6	1960	4.39	1.6	8.25	13.0
7	2287	5.17	1.4	10.50	13.9
8	2566	5.72	1.2	13.25	16.0

The data of Table 16 are presented in Fig. 72 to show the relation of length of the wetted strip and area of land covered by the 2.28 cfs stream (columns 1 and 2) to the time periods of column 5. The curve of Fig. 72 is typical and shows maximum rate of advance of the stream near the beginning of irrigation and minimum rate near the end. For example, in the first 2 hr the advance of the stream was nearly 500 ft and in the last 2 hr only about 75 ft.

For assumed constant rate of infiltration, I, and depths of sheet of

water, y, curves based on computations with equation 28, showing the relation of wetted area of land covered, to the several time periods, are not closely related to the curve of Fig. 72 and are not presented here.

The experimental data for the clover tract have been analyzed to estimate the infiltration rates. With $q = 2.28$ cfs, using equation 29a, and values of A and t taken from Fig. 72, the computed values of I range from 4 in./hr when $t = 2$ hr down to 0.85 in./hr when $t = 23.7$ hr.



Point on curve	Wetted area A	Infiltration Rate I
1	0.55	4.0
2	0.75	3.0
3	1.13	2.0
4	1.34	1.7
5	2.00	1.1
6	2.26	1.0
7	2.50	0.9
8	2.68	0.8

Fig. 72. Relation between distance and time of water flow on a border strip of 49 ft width near Rigby, Idaho, with a constant inflow of 2.28 cfs.

Table 17 shows the wetted areas, infiltration rates and quantities of water that were percolating into the wetted soil at the different time periods. Since a stream of 2.28 cfs was applied to the strip, column 5 shows that only 0.08 cfs was flowing past the 0.55-acre area 2 hr after irrigation was begun. It follows that, when the average depth of irrigation was 8.3 in., 96.5 percent of the stream was percolating into the soil and 3.5 flowing on to the dry soil. Moreover, after the first 3 hr, when only 36 percent of the border strip was wetted, only a negligible 0.03 cfs would have flowed beyond the wetted soil if the infiltration rate had remained constant. For more than 20 hr the advance of the stream was dependent on the decrease of rate of infiltration with time.

The time rate of advance of stream of various sizes has been

TABLE 17

Relations of Length of Wetted Border Strip, Area Covered with Water, and Time Periods to Infiltration Rates, in the Clover Tract of Table 16

1	2	3	4	5
Length Wetted Strip, Feet	Wetted Area, Acres	Time of Flow, Hours	Rates of Infiltration, In./Hr	Water Flow into Soil = Area × Infiltration Rate, Cfs
440	0.55	2	4.0	2.200
674	0.75	3	3.0	2.250
1011	1.13	5	2.0	2.260
1180	1.34	8	1.7	2.278
1760	2.00	12	1.1	2.280
1990	2.26	15.5	1.0	2.260
2200	2.50	20	0.9	2.275
2360	2.68	23.7	0.8	2.278

developed by Criddle. For a typical soil of uniform furrow slope, this rate is shown for four streams in Fig. 73.

A stream of 2 gpm in one furrow, for example, advanced very slowly after the first 25 min. In 100 min this stream flowed a distance

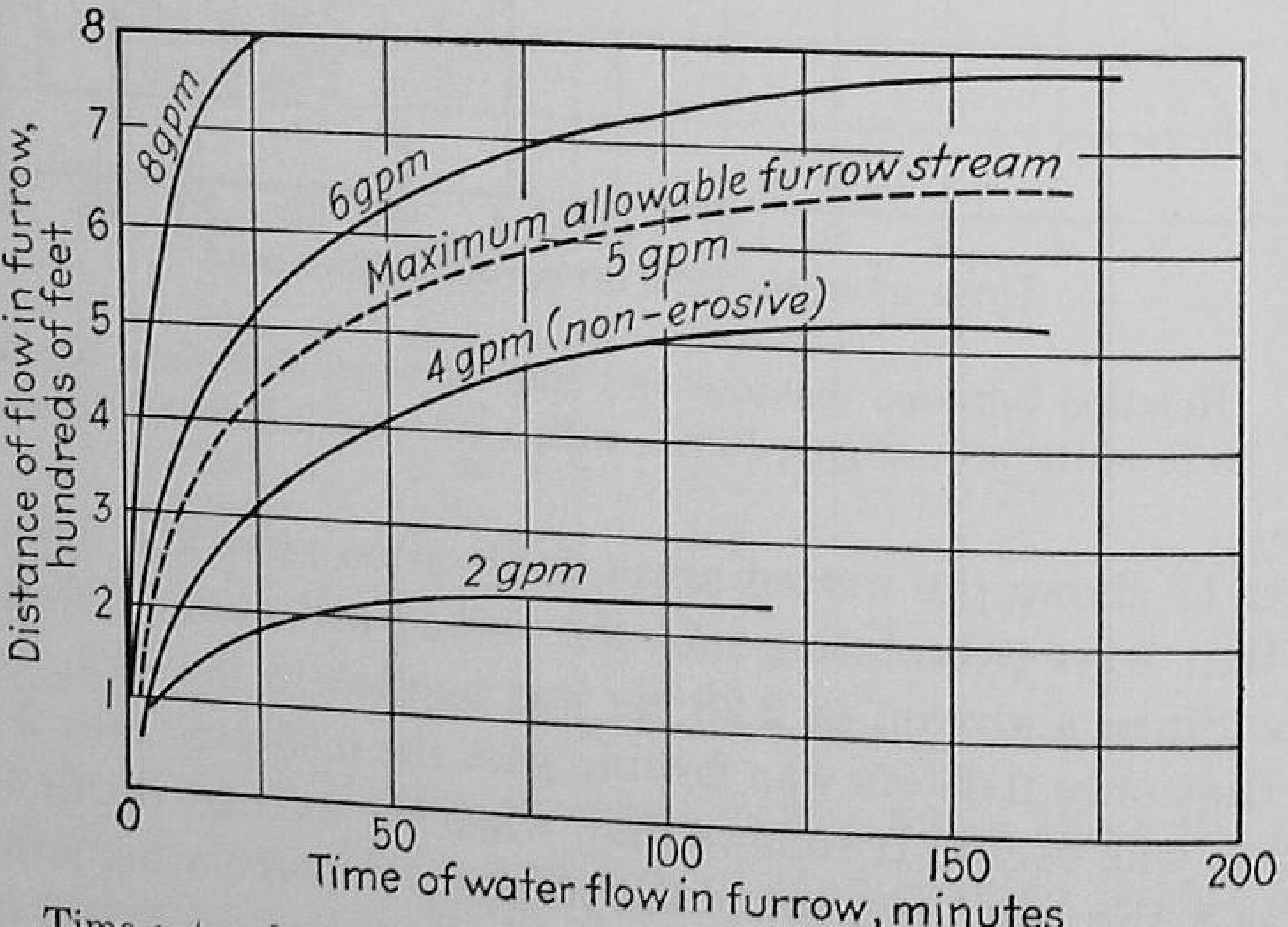


Fig. 73. Time rate of advance for furrow streams of different sizes on a typical soil of uniform furrow slope. (Courtesy Soil Conservation Service.)

of 225 ft, approximately, and thereafter the entire stream percolated into the soil of the 225-ft furrow. Criddle properly stresses the importance of erosion control. Water losses due to excess percolation

as a result of low time rates of water application are less serious on many farms than soil-erosion losses due to large streams and excessive slopes. The maximum allowable furrow stream of 5 gpm, equivalent to 90 furrows per cfs, flowed a distance of about 630 ft in 2 hr. Furrows longer than 225 ft, in the soil on which Criddle experimented, could not be used for streams of 2 gpm or less without sustaining excessive deep percolation losses and low water application efficiencies. Likewise the results of other experiments stress the fact that with highly permeable soils irrigation water must be applied in large streams to

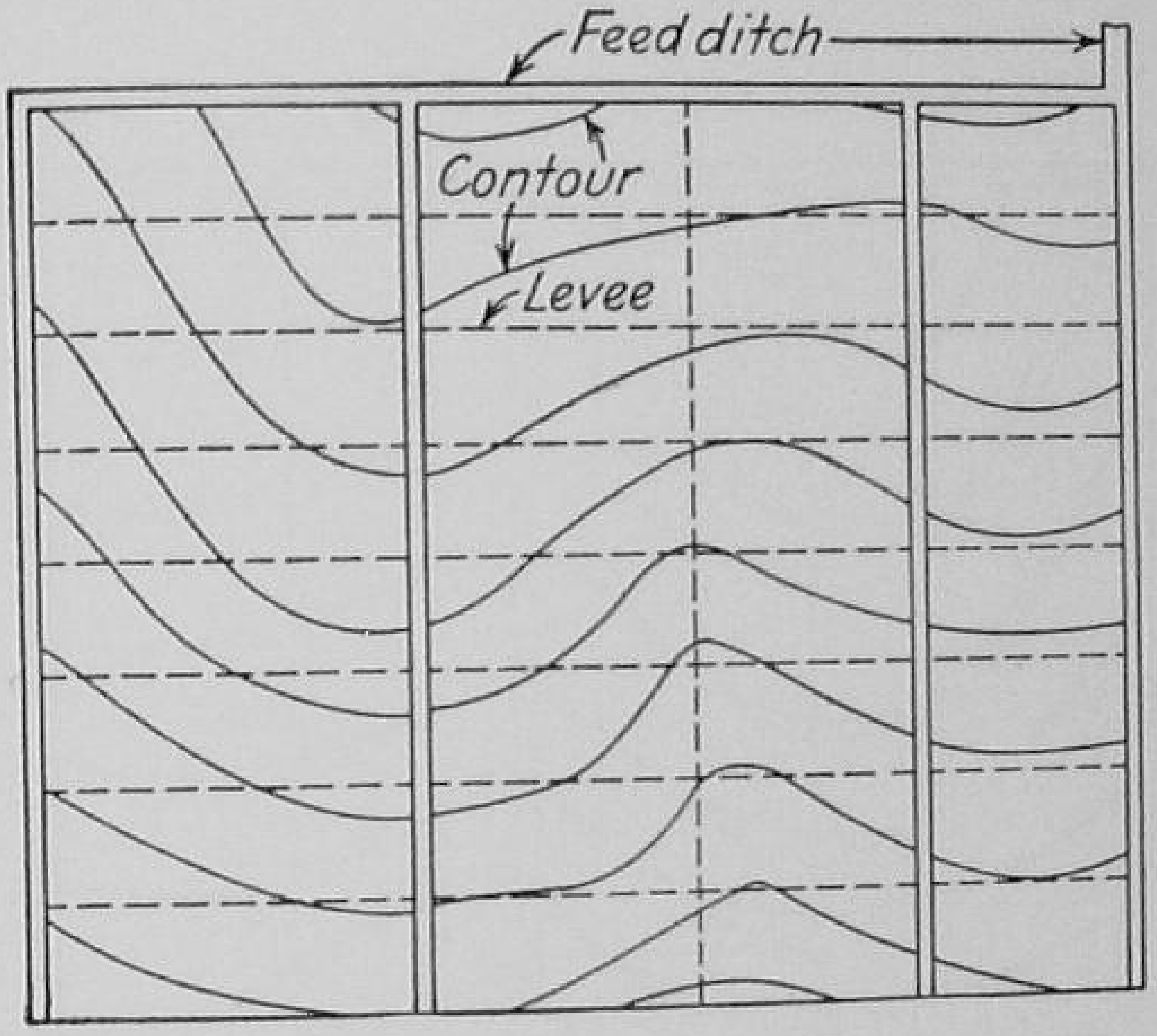


FIG. 74*A*. Field showing rectangular checks.

small plots in order to prevent excessive deep percolation losses. Canal company water deliveries, farm ditches, and land preparation for such soils must be so planned that irrigators may apply water at a high time rate (q/A) allowable for erosion control, probably from 10 to 25 cfs per acre, to avoid excessive deep percolation. For example, a stream of 4 cfs, applied to a ⅕-acre plot, gives a time rate of 20 cfs per acre. Continuous and intelligent efforts are essential in the border-strip method to obtain efficient water application without causing excessive erosions. A formula for border-strip irrigation, based on mathematical analysis of experimental data, has been developed by Goodrich. Advanced students will find these analyses and resulting formulas interesting.

80. Check Flooding The check-flooding method consists of running comparatively large streams into relatively level plots surrounded by levees. This method, shown in Fig. 74*A*, is well suited to very permeable soils which must be quickly covered with water in order to prevent excessive losses near the supply ditches through deep per-

colation. It is also suited to heavy soils into which water percolates so slowly that they are not sufficiently moistened during the time a sheet of water flows over them, making it necessary to hold the water on the surface to assure adequate penetration.

Checks are sometimes prepared by constructing levees along contours having vertical intervals of 0.2 to 0.4 ft and connecting them with cross levees at convenient places. These are called contour checks and are formed by building longitudinal levees on straight lines approximately parallel to the contours, and connecting them at desirable places with levees at right angles, as shown in Fig. 74*B*.

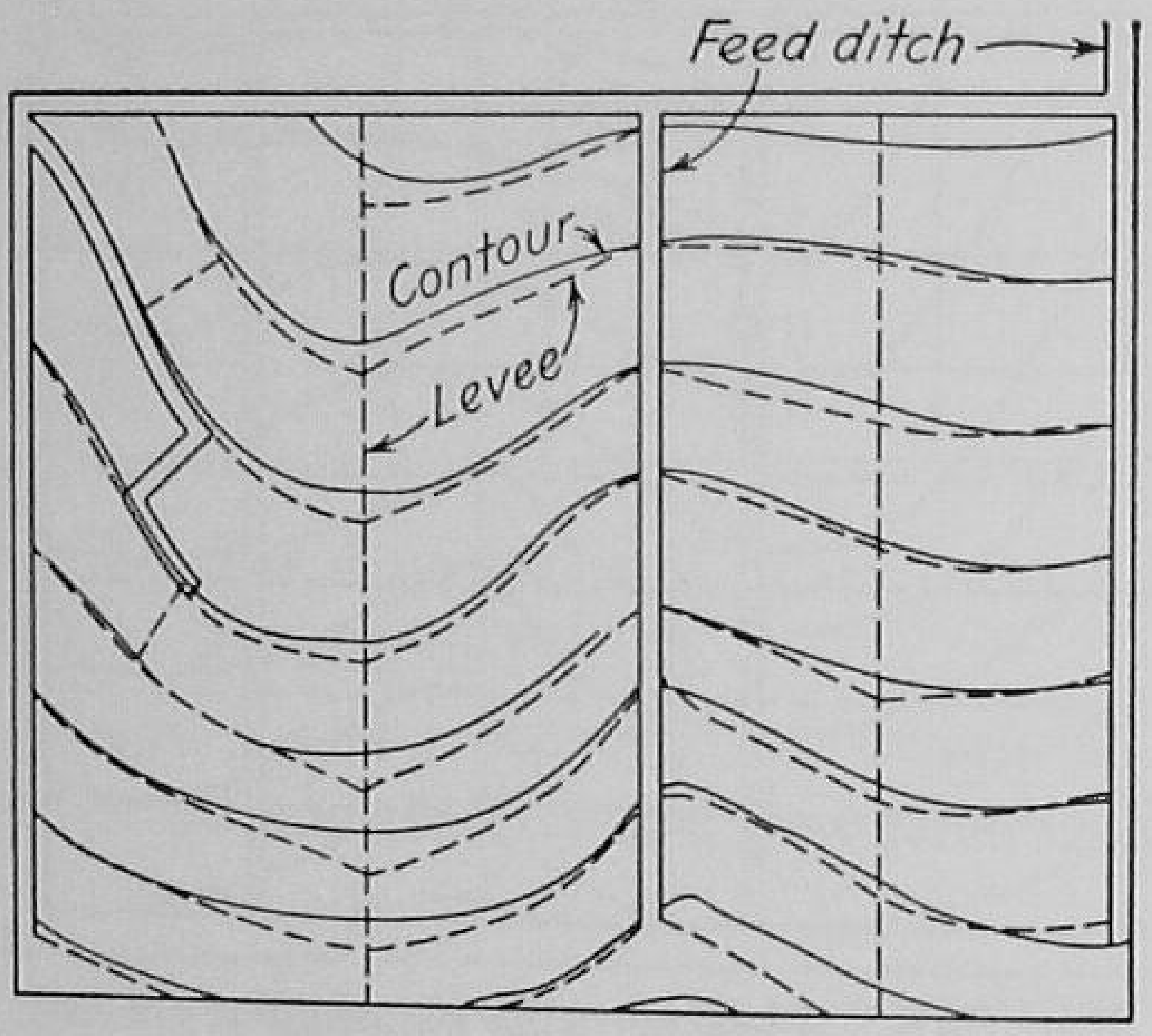


FIG. 74*B*. Contour checks on same field as in Fig. 74*A*.

The check method of irrigation for grain and forage crops is advantageous in localities where large irrigation streams are available and also on projects which depend on direct flow from widely fluctuating streams. In Arizona, New Mexico, and Nevada, torrential summer rains suddenly make swollen streams which must be quickly applied to the land to prevent loss of the water. On land of very small slopes the area of each check may be several acres. In general, checks larger than 2½ to 3 acres are considered less desirable than checks from ½ to 2 acres.

The levees should be from 6 to 8 ft wide at the base and not over 10 to 12 in. high because it is essential to avoid obstruction to farm machinery, and also to assure satisfactory growth of crops on the levees.

81. Basin Flooding The basin method of flooding is essentially the check method especially adapted to irrigation of orchards. On some farms a basin is made for each tree, but under favorable conditions of

soil and surface slope from 2 to 5 or more trees are included in one basin. From the supply ditch the water is conveyed to the basin, either by flowing through one basin and into another, or preferably by small ditches constructed so that the water may be turned directly from a ditch into each basin. This method is considered more fully in Chapter 16.

82. Distribution of Water To irrigate efficiently it is essential to distribute water uniformly, to avoid ponding and excessive deep percolation losses on one part of the field and inadequate wetting of the soil on another part. The objective in each irrigation is to moisten the soil fully without permitting excessive deep percolation losses from the root-zone soil in any part of the field. Large surface runoff losses at the lower part of the field are wasteful, but these losses are so easily detected and prevented that little attention need be given them here. The desired objective is difficult to attain, particularly with those flooding methods in which the soil is wetted by causing a sheet of water to flow slowly over the land surface.

83. Estimation of Water Disposal If the irrigator knows the size of stream delivered to his farm he can compute the average depth of water applied to a given area of land in a certain time. To illustrate:

Let q = the size of stream in cubic feet per second (or acre-inches per hour).
a = the area, in acres.
t = the time in hours required to irrigate the area.
d = the depth in inches that the volume of water used would cover the land irrigated if quickly spread uniformly over its surface.

The quantity in cubic feet per second (or acre-inches per hour) multiplied by the time in hours equals the acre-inches applied. Also the number of acres covered, times the depth, in inches, equals the acre-inches applied. Hence

$$da = qt \tag{30}$$

If the irrigator knows any three of the above quantities he can determine the other one. For convenience, Tables 18, 19, and 20, which appear on pages 132, 133, and 134, all of which are based on equation 30, may be used to determine directly for a 1-acre tract either the depth, d, size of stream, q, or time in hours, t, respectively, when each of the other factors is known. For example, Table 18 shows that a stream of 1.8 cfs running 3 hr should uniformly cover 1 acre to a depth, d, of 5.4 in. Table 19 shows that to cover 1 acre uniformly to a depth of

TABLE 18

DEPTH IN INCHES THAT A STREAM, q cfs, FLOWING t HOURS, WOULD COVER 1 ACRE IF SPREAD UNIFORMLY

BASED ON EQUATION 30, $d = \frac{qt}{a}$

Line No.	Discharge c f s q	Time in Hours, t											
		1	2	3	4	5	6	7	8	9	10	11	12
1	0.5	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
2	.6	.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4	6.0	6.6	7.2
3	.7	.7	1.4	2.1	2.8	3.5	4.2	4.9	5.6	6.3	7.0	7.7	8.4
4	.8	.8	1.6	2.4	3.2	4.0	4.8	5.6	6.4	7.2	8.0	8.8	9.6
5	.9	.9	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1	9.0	9.9	10.8
6	1.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
7	1.2	1.2	2.4	3.6	4.8	6.0	7.2	8.4	9.6	10.8	12.0	13.2	14.4
8	1.4	1.4	2.8	4.2	5.6	7.0	8.4	9.8	11.2	12.6	14.0	15.4	16.8
9	1.6	1.6	3.2	4.8	6.4	8.0	9.6	11.2	12.8	14.4	16.0	17.6	19.2
10	1.8	1.8	3.6	5.4	7.2	9.0	10.8	12.6	14.4	16.2	18.0	19.8	21.6
11	2.0	2.0	4.0	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0	22.0	24.0
12	2.2	2.2	4.4	6.6	8.8	11.0	13.2	15.4	17.6	19.8	22.0	24.2	26.4
13	2.4	2.4	4.8	7.2	9.6	12.0	14.4	16.8	19.2	21.6	24.0	26.4	28.8
14	2.6	2.6	5.2	7.8	10.4	13.0	15.6	18.2	20.8	23.4	26.0	28.6	31.2
15	2.8	2.8	5.6	8 4	11.2	14.0	16.8	19.6	22.4	25.2	28.0	30.8	33.6
16	3.0	3.0	6.0	9.0	12.0	15.0	18.0	21.0	24.0	27.0	30.0	33.0	36.0
17	3.2	3.2	6.4	9.6	12.8	16.0	19.2	22.4	25.6	28.8	32.0	35.2	38.4
18	3.4	3.4	6.8	10.2	15.6	17.0	20.4	23.8	27.2	30.6	34.0	37.4	40.8
19	3.6	3.6	7.2	10.8	14.4	18.0	21.6	25.2	28.8	32.4	36.0	39.6	43.2
20	3.8	3.8	7.6	11.4	15.2	19.0	22.8	26.6	30.4	34.2	38.0	41.8	45.6
21	4.0	4.0	8.0	12.0	16.0	20.0	24.0	28.0	32.0	36.0	40.0	44.0	48.0
22	4.2	4.2	8.4	12.6	16.8	21.0	25.2	29.4	33.6	37.8	42.0	46.2	50.4
23	4.4	4.4	8.8	13.2	17.6	22.0	26.4	30.8	35.2	39.6	44.0	48.4	52.8
24	4.6	4.6	9.2	13.8	18.4	23.0	27.6	32.2	36.8	41.4	46.0	50.6	55.2
25	4.8	4.8	9.6	14.4	19.2	24.0	28.8	33.6	38.4	43.2	48.0	52.8	57.6
26	5.0	5.0	10.0	15.0	20.0	25.0	30.0	35.0	40.0	45.0	50.0	55.0	60.0

TABLE 19

SIZE OF STREAM, q cfs, FLOWING t HOURS REQUIRED TO APPLY A DEPTH d INCHES OF IRRIGATION WATER TO 1 ACRE IF SPREAD UNIFORMLY

BASED ON EQUATION 30, $q = \frac{da}{t}$

Line No.	Depth in Inches d	Time in Hours, t											
		1	2	3	4	5	6	7	8	9	10	11	12
1	1.0	1.00	0.50	0.33	0.25	0.20	0.17	0.14	0.125	0.11	0.10	0.091	0.083
2	1.5	1.50	0.75	.50	.37	.30	.25	.21	.19	.17	.15	.146	.125
3	2.0	2.00	1.00	.67	.50	.40	.33	.29	.25	.22	.20	.18	.17
4	2.5	2.50	1.25	.83	.62	.50	.41	.36	.31	.28	.25	.23	.20
5	3.0	3.00	1.50	1.00	.75	.60	.50	.43	.37	.33	.30	.27	.25
6	3.5	3.50	1.75	1.18	.88	.70	.58	.50	.44	.39	.35	.32	.29
7	4.0	4.00	2.00	1.33	1.00	.80	.67	.57	.50	.44	.40	.36	.33
8	4.5	4.50	2.25	1.50	1.12	.90	.75	.64	.56	.50	.45	.41	.37
9	5.0	5.00	2.50	1.67	1.25	1.00	.83	.71	.62	.56	.50	.45	.42
10	5.5	5.50	2.75	1.83	1.37	1.10	.92	.79	.69	.61	.55	.50	.46
11	6.0	6.00	3.00	2.00	1.50	1.20	1.00	.86	.75	.67	.60	.55	.50
12	6.5	6.50	3.25	2.16	1.62	1.30	1.08	.93	.81	.72	.65	.59	.54
13	7.0	7.00	3.50	2.33	1.75	1.40	1.18	1.00	.88	.78	.70	.64	.58
14	7.5	7.50	3.75	2.50	1.87	1.50	1.25	1.07	.94	.84	.75	.68	.63
15	8.0	8.00	4.00	2.67	2.00	1.60	1.33	1.14	1.00	.89	.80	.73	.67
16	8.5	8.50	4.25	2.83	2.12	1.70	1.42	1.21	1.06	.95	.85	.77	.71
17	9.0	9.00	4.50	3.00	2.25	1.80	1.50	1.29	1.13	1.00	.90	.82	.75
18	9.5	9.50	4.75	3.16	2.38	1.90	1.58	1.36	1.19	1.06	.95	.86	.79
19	10.0	10.00	5.00	3.33	2.50	2.00	1.67	1.43	1.25	1.11	1.00	.91	.83
20	10.5	10.50	5.25	3.50	2.64	2.10	1.75	1.50	1.31	1.17	1.05	.95	.88
21	11.0	11.00	5.50	3.67	2.75	2.20	1.83	1.57	1.38	1.22	1.10	1.00	.92
22	11.5	11.50	5.75	3.83	2.87	2.30	1.92	1.64	1.44	1.28	1.15	1.05	.96
23	12.0	12.00	6.00	4.00	3.00	2.40	2.00	1.71	1.50	1.34	1.20	1.09	1.00

TABLE 20

Time in Hours, t, Required with a Stream, q cfs, to Apply d Inches of Irrigation Water to 1 Acre if Spread Uniformly

Based on Equation 30, $t = \frac{da}{q}$

Line No.	Discharge c f s q	Depth in Inches, d											
		1	2	3	4	5	6	7	8	9	10	11	12
1	0.5	2.00	4.00	6.00	8.0	10.00	12.0	14.00	16.00	18.00	20.00	22.00	24.00
2	.6	1.66	3.33	5.00	6.67	8.33	10.0	11.67	13.33	15.00	16.67	18.33	20.00
3	.7	1.43	2.86	4.30	5.72	7.15	8.58	10.00	11.43	12.86	14.33	15.73	17.17
4	.8	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50	13.76	15.00
5	.9	1.11	2.22	3.33	4.50	5.56	6.68	7.78	8.88	10.00	11.10	12.25	13.33
6	1.0	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00
7	1.2	.84	1.67	2.50	3.33	4.16	5.00	5.84	6.67	7.50	8.33	9.17	10.00
8	1.4	.71	1.43	2.14	2.86	3.57	4.28	5.00	5.71	6.43	7.14	7.87	8.57
9	1.6	.63	1.25	1.87	2.50	3.13	3.75	4.38	5.00	5.62	6.25	6.88	7.50
10	1.8	.56	1.11	1.67	2.22	2.78	3.33	3.88	4.44	5.00	5.55	6.12	6.67
11	2.0	.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00
12	2.2	.45	.91	1.36	1.82	2.27	2.73	3.18	3.64	4.09	4.54	5.00	5.46
13	2.4	.42	.83	1.25	1.67	2.08	2.50	2.92	3.33	3.75	4.16	4.58	5.00
14	2.6	.38	.77	1.15	1.54	1.92	2.31	2.69	3.08	3.46	3.85	4.23	4.62
15	2.8	.36	.71	1.07	1.43	1.78	2.14	2.50	2.86	3.22	3.57	3.93	4.28
16	3.0	.33	.67	1.00	1.33	1.67	2.00	2.33	2.67	3.00	3.33	3.67	4.00
17	3.2	.31	.63	.94	1.25	1.56	1.88	2.19	2.50	2.81	3.12	3.44	3.75
18	3.4	.29	.59	.88	1.18	1.47	1.76	2.06	2.35	2.65	2.94	3.24	3.53
19	3.6	.28	.56	.83	1.11	1.39	1.67	1.94	2.22	2.50	2.78	3.06	3.33
20	3.8	.26	.55	.79	1.05	1.32	1.58	1.84	2.10	2.37	2.63	2.90	3.16
21	4.0	.25	.50	.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75	3.00
22	4.2	.24	.48	.71	.95	1.19	1.43	1.67	1.90	2.14	2.38	2.62	2.86
23	4.4	.23	.45	.68	.91	1.14	1.36	1.59	1.82	2.04	2.27	2.50	2.73
24	4.6	.22	.44	.65	.87	1.09	1.30	1.52	1.74	1.96	2.17	2.39	2.61
25	4.8	.21	.42	.63	.83	1.04	1.25	1.46	1.67	1.88	2.08	2.29	2.50
26	5.0	.20	.40	.60	.80	1.00	1.20	1.40	1.60	1.80	2.00	2.20	2.40

6 in. in 5 hr should require a stream of 1.20 cfs. Table 20 shows that with a stream of 2.0 cfs it should require 3.5 hr to supply enough water to cover 1 acre to a depth of 7 in.

In Chapter 9 it is shown that ordinary soils seldom retain an average of more than 1 acre-inch of water in each acre-foot of root zone soil from a single irrigation. Consider, for example, bench-land soil 4 ft

FIG. 75. Furrow irrigation in Snake River Valley, Idaho. (Photographer unknown.)

in depth underlain by coarse sand and gravel. If the irrigator finds that under the method he is using it takes 4 hr to irrigate 1 acre using a stream of 2.8 cfs, he may determine from equation 30 or Table 18 that he has applied enough water to cover the land to a depth of 11.2 in. Since the root-zone soil will hold only 4 acre-inches, the irrigator sustains a deep percolation loss of over 7 acre-inches. He must modify his method of application in order to apply water more efficiently.

84. The Furrow Method In the irrigation methods thus far described, almost the entire land surface is wetted in each irrigation. Using furrows for irrigation, as shown in Fig. 75, necessitates the wetting of

only a part of the surface (from one-half to one-fifth) thus reducing evaporation losses, lessening the puddling of heavy soils, and making it possible to cultivate the soil sooner after irrigation.

Nearly all row crops are irrigated by the furrow method. In Washington, parts of Idaho, and southern Utah, grain and alfalfa crops are irrigated by means of small furrows designated corrugations. These corrugations are advantageous when the available irrigation streams are small, and also for land of uneven topography. Furrow irrigation is adaptable to a great variation in slope. It is customary, although on steep slopes inadvisable, to run the furrows down the steepest slope, thus avoiding inconvenience due to overflowing the banks of the furrows.

85. Length of Furrows On some soils, furrows having slopes of 100 to 150 ft per 1000 ft are successfully used by allowing only very small streams to enter the furrow and by careful inspection to control erosion. Slopes of 10 to 30 ft per 1000 are preferable, but many different classes of soil are satisfactorily irrigated with furrow slope from 30 to 60 ft per 1000 ft.

The length of furrows varies from 100 ft or less for gardens to as much as ¼ mile for field crops. In Utah, very few irrigators use furrows more than 660 ft; lengths of 300 to 500 ft are far more common. Excessive deep percolation losses and soil erosion near the upper end of the field result from use of long furrows.

86. Spacing and Depths of Furrows Spacing of furrows for irrigation of corn, potatoes, sugar beets, and other row crops is determined by the proper spacing of the plant rows, one irrigation furrow being provided for each row. In orchard irrigation, furrows may be spaced from 3 to 6 ft apart. Soils having unusually favorable capillary properties, or impervious subsoils, may permit orchard furrows 10 to 12 ft apart. With the greater spacing it is essential to check on the moisture distribution after each irrigation by making borings with a soil auger or tube to find whether or not the lateral moisture movement from furrows is adequate.

Furrows from 8 to 12 in. deep facilitate control of water and penetration into soils of low permeability. They are well suited to orchards and to some furrow crops. Other furrow crops as sugar beets are best irrigated with furrows from 3 to 5 in. deep. It is highly desirable in irrigating sugar beets and similar root crops to have the furrows deep enough, and the stream in each small enough, so that the water cannot come in contact with the plant.

87. Water Distribution to Furrows Water is distributed to the furrows from earth supply ditches or from wood or concrete flumes or concrete pipe placed under ground. In Utah and Idaho the earth supply ditch is most common. Small openings are made through the bank, and the water flows into one or more furrows. Figure 76 shows four small ditches or corrugations supplied from a single outlet. This method necessitates careful supervision to avoid erosion of the supply ditch openings, and consequent excess flow in some and inadequate

FIG. 76. Four corrugations supplied from single outlet. (*U.S.D.A. Farmers' Bul.* 1348.)

flow in others. On the other hand, it provides flexibility, permitting a large stream in each furrow when the water is first turned in, thus wetting the furrow through its entire length quickly, and then decreasing it so that just enough water enters the furrow to keep it wet, and at the same time reducing the runoff from the lower end to a minimum, or preventing it entirely.

The use of small-diameter 48-in. length curved pipe, made of lightweight cellulose, aluminum, galvanized iron, or rubber, enables the irrigator to siphon water from the ditch to the furrows as shown in Fig. 77 and keep ditch banks solid. This method has more flexibility and permits easy and frequent change of application of water from furrow to furrow.

Irrigators can increase the uniformity of application of water to their furrow-irrigated crops by frequent regulation of the size of stream flowing into the furrow. For this purpose, gated pipe, shown

Fig. 77. Plastic siphon tubes used in furrow irrigation. (Courtesy Soil Conservation Service.)

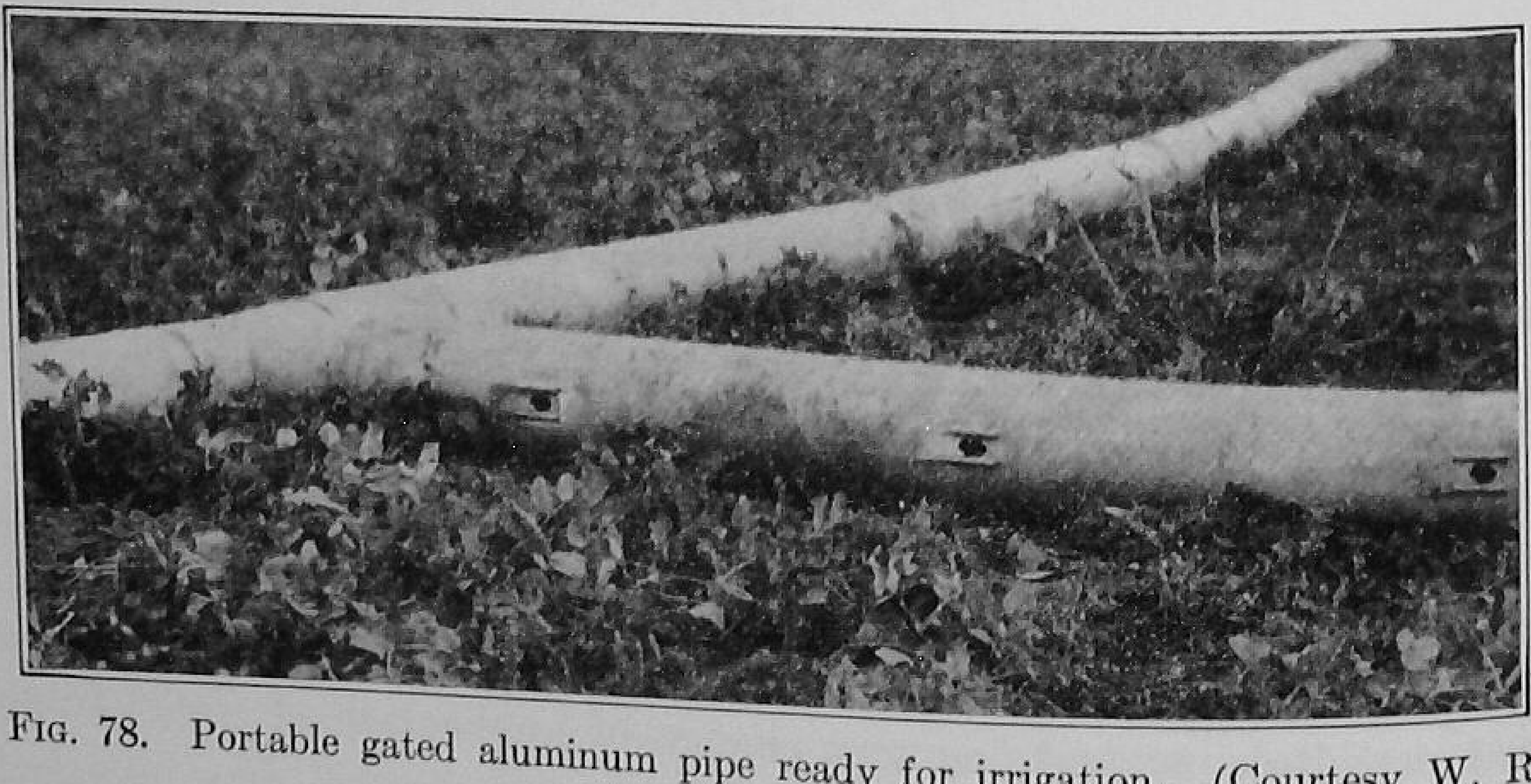


Fig. 78. Portable gated aluminum pipe ready for irrigation. (Courtesy W. R. Ames Company.)

in Fig. 78, is especially helpful. The use of gated pipe is increasing substantially.

Small, easily adjusted gates in the pipe facilitate control of the size of stream delivered to the furrow. Streams as small as 1 gpm or as large as 10 gpm or more can be delivered. The lightweight aluminum or galvanized gated pipe is easily placed, easily connected, and easily moved after irrigation.

88. Natural Sub-Irrigation In a few localities, natural soil and topographic conditions are favorable to the application of water to soils directly under the surface, a practice known as sub-irrigation. An impervious subsoil at a depth of 6 ft or more, a highly permeable loam or sandy loam surface soil, uniform topographic conditions, and moderate slopes favor sub-irrigation. Under such conditions, proper water control to prevent alkali accumulation or excess waterlogging usually results in economical use of water, high crop yields, and low labor cost in irrigation.

California has several large tracts of low-lying lands in the Sacramento-San Joaquin Delta that are successfully sub-irrigated. Before being reclaimed some of these tracts were flooded every year by the overflow waters of the Sacramento and San Joaquin rivers. Reclamation was made possible by building large levees around tracts of several thousands of acres, followed by installing drainage systems and by pumping the water discharged from the drains over the levees into the river channels. The soils are composed largely of decayed organic matter and are known as peat, tule, or muck soils. During several months of each year, the water in the river channels, now controlled by artificial levees, is 2 to 10 ft or more higher than the land surface. In order to obtain water for irrigation, siphons are built from the channels over the levees and the water is thus siphoned to the lands. It is distributed in a series of ditches from 2 to 3 ft deep and 1 ft wide having vertical sides. These ditches, spaced from 150 to 300 ft apart, provide adequate distribution of the water satisfactorily for irrigation of small grains and root crops.

Some of these sub-irrigated California delta-area lands have been injured and made less productive by saline and alkali conditions developed by the upward capillary water flow from the shallow water table. This reduction in productivity has made it necessary to discontinue sub-irrigation and irrigate large areas by the sprinkling method.

In the mountain states there are three notable areas on which natural sub-irrigation is successfully practiced, namely: the Egin

Bench area in upper Snake River Valley, Idaho; Cache Valley, Utah; and San Luis Valley, Colorado. The conditions and procedure in the application of water are typified by the Egin Bench, Snake River Valley practice, which is described below.

89. Sub-Irrigation on Egin Bench, Idaho The land slopes uniformly about 2 ft per 1000 ft. Surface loams and gravelly loams from 1.5 to 6 ft in depth are underlain by more permeable soil materials which rest on impervious lava rock at depths varying from a few feet to as much as 90 ft.

Clinton describes some of the noteworthy facts of this Egin Bench 28,000-acre sub-irrigated tract somewhat as follows.

The flow of water in the main canals is regulated by a ditchrider, whose job is very different from that of his co-worker on a conventional irrigation system. Essentially he is operating a huge ground-water reservoir, the water level of which is controlled by the rate of inflow and outflow. The inflow is from controlled water supplies and precipitation; the outflow, consumptive use by plants, evaporation from the soil, and seepage. Excess inflow means waterlogged soils, flooded fields, farmyards, and roads, while excess outflow results in wilted crops.

Irrigation does not interrupt cultivation of fields. Farm machinery can be operated in the fields at any time, even though the water table is near the ground surface.

The principal crops grown on the Egin Bench are, in order of percentage of cropped area, potatoes, alfalfa and clover hay, small grains, sugar beets, and field peas. Early in the agricultural development of the area, an attempt was made to irrigate the land by the usual flooding methods. Excessive deep percolation losses resulted, and frequent irrigation was found essential to ordinary crop yields. The gradual rise of the water table convinced the irrigators that smaller quantities of water would suffice under more favorable irrigation methods. Irrigation water is applied in shallow ditches about 3 ft wide and spaced from 100 to 300 ft apart. In general, these ditches do not exceed ¼ mile in length. A stream from ¼ to ½ cfs is run into each ditch, from which it sinks to the ground water, causing the water table to rise high enough to moisten the root-zone soil by capillary action and thus fully supply the water needs of the growing crops.

90. Sub-Irrigation and Drainage In some localities, natural drainage is insufficient to carry away the excess water applied in sub-irrigation. It has been found necessary in the Lewiston Area, Cache Valley, Utah. to construct large open drains to prevent excessive waterlogging

and salinity of soils. In certain favorable parts of large irrigated valleys such as the San Joaquin Valley, California, and the Salt River Valley, Arizona, where deep percolation from the flooding irrigation methods has resulted in the rise of the ground water to the extent that drainage by pumping has been found essential to maintain the soil productivity, it is possible that sub-irrigation methods may advantageously be employed.

91. Artificial Sub-Irrigation Under favorable soil conditions for the production of high-priced crops on small areas a pipe distribution system is placed in the soil well beneath the surface. The process of applying water beneath the soil surface through various kinds of pipes or other conduits is designated artificial sub-irrigation. Favorable soil conditions which permit free lateral movement of water, and relatively rapid capillary movement in the root-zone soil, and very slow downward movement in the subsoil, are essential to the mechanical success of artificial sub-irrigation. Persons not informed concerning the several methods of irrigation are sometimes prone to overvalue the advantages of artificial sub-irrigation and make expenditures far greater than economic results justify. The cost of this method of irrigation is usually prohibitive.

92. Sprinkler Irrigation The method of applying water to the surface of the soil in the form of a spray, somewhat as in ordinary rain, has been found practical. This method is known as sprinkling.

Sprinkling as a method of irrigation was started about 1900. The first agricultural sprinkler systems were an outgrowth of city lawn sprinkling. Before 1920 sprinkling was limited to truck crops, nurseries, and orchards.

It was used in humid regions as a supplemental method of irrigation. Most of these systems were stationary overhead perforated pipe installations, or stationary overtree systems with rotating sprinklers. These systems were expensive to install but often fairly inexpensive to operate. Portable sprinkler systems developed with the introduction of lightweight steel pipe and quick couplers in the early 1930's. This reduced the equipment cost for sprinkler systems and resulted in an increased number of sprinkler installations. The early development occurred principally in the Sacramento Valley of California. Owing to the development of more efficient sprinklers, lightweight aluminum pipe, and more efficient pumps, and to the widespread distribution of electrical power, the number of sprinkler installations has increased rapidly since World War II.

Sprinklers have been used on all soil types, on lands of widely

different topography and slopes, and for many crops. Sprinklers are especially desirable to irrigate soils having high infiltration rates, shallow soils the topography of which prevents proper leveling for surface irrigation methods, and areas having steep slopes and erosible soils. Under these conditions sprinklers save water, labor, and soil and usually increase crop production over any other method.

93. Purposes of Sprinkler Systems Sprinkler irrigation systems may be divided into three groups according to the purpose for which they are used: (1) the main irrigation system, (2) the supplemental irrigation system, and (3) the protective irrigation system.

In arid regions, where all crops depend on irrigation, sprinkler systems are used to apply all the water used by the crops grown. The design of such a system must be based on the available water-holding capacity of the soil and on the peak rate of consumptive use of the crop. Sufficient equipment must be available to cover the given area in the time calculated from the above two factors.

In some areas where the natural rainfall is usually adequate to supply crop needs there are times when additional water during short drought periods is essential to obtain normal crop returns. Perhaps but one water application is needed. This is called supplemental irrigation.

Systems for protective purposes are illustrated by those used on the cranberry bogs of the Northwest to keep the crop from being damaged by freezing weather.

94. Types of Sprinklers Four types of sprinklers used in present-day sprinkler irrigation systems are:

(*a*) Perforated pipe (Perf-O-Rain).
(*b*) Fixed nozzle attached to pipes (Skinner).
(*c*) Rotating-head sprinklers.
(*d*) Fixed-head sprinklers.

The earlier sprinkler systems were "perforated pipe" or "fixed nozzle pipe" types. These systems are used today in the eastern United States. Parallel pipes are installed about 50 ft apart and supported on rows of posts. Water is discharged at right angles perpendicularly from the pipe line. The entire 50-ft width between pipe lines may be irrigated by turning the pipes through about 135°. Figure 79 illustrates this method.

The rotating-head or circular-spray sprinklers illustrated in Fig. 80 are coming into favor since the development of the lightweight portable

FIG. 79. Standard overhead sprinkling irrigation system. (Courtesy Skinner Irrigation Company.)

FIG. 80. Sprinkler system on 400-acre field of tomatoes near Sacramento, California. (Courtesy Shur-Rane Irrigation Company and E. C. Olsen Company.)

quick-coupler pipe. The advantage of this sprinkler over other types is its ability to apply water at a slow rate while using relatively large nozzle openings. This factor is particularly favorable in waters containing silt and debris since less stoppage of sprinklers is experienced. Application rates of 0.2 in. per hr are minimum rates with rotating sprinklers, while the minimum rate with perforated pipe is 1.0 in. per hr. This slow rate is desirable on soils of low infiltration rates

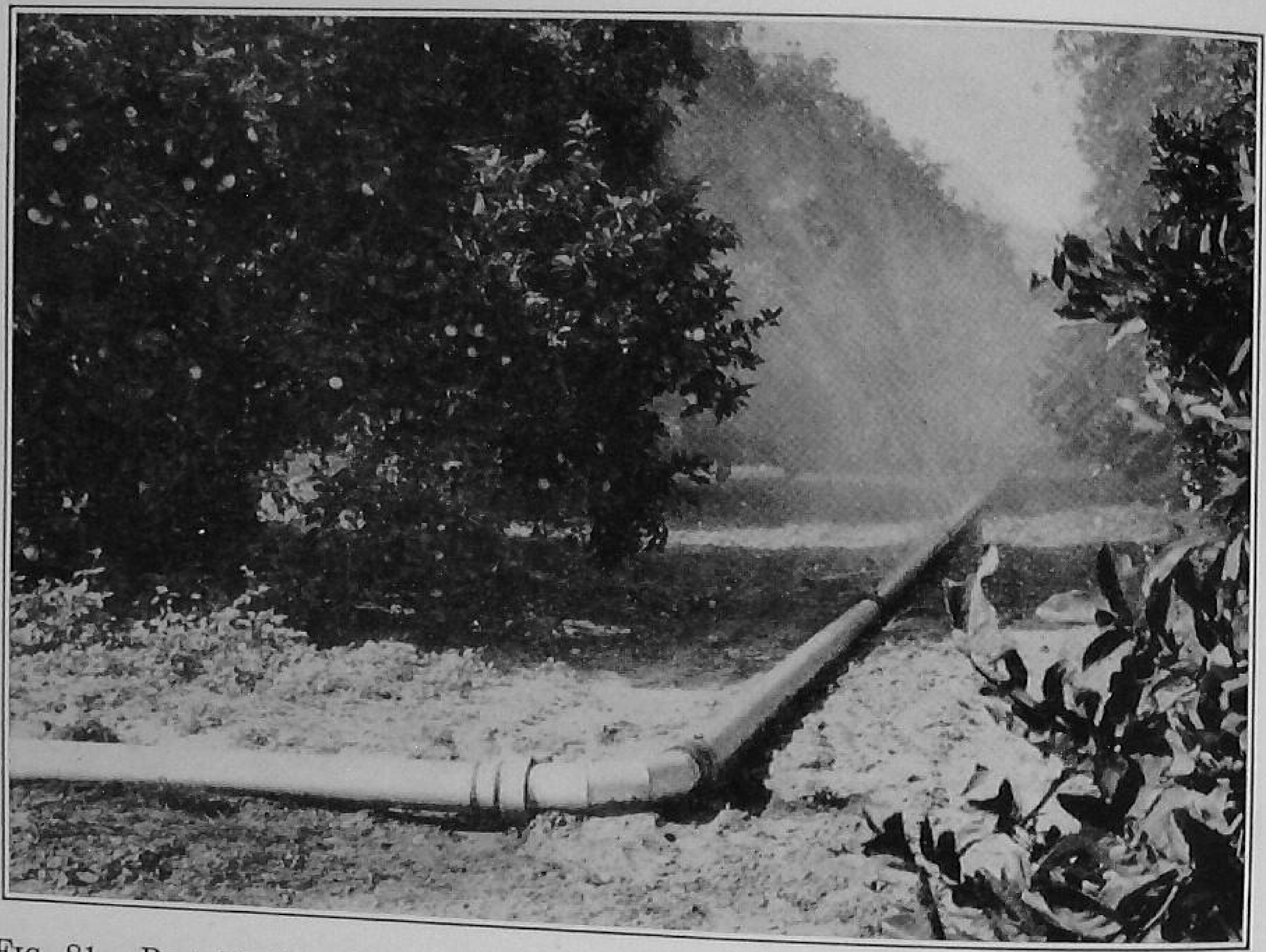


FIG. 81. Portable fixed-head sprinkling system in citrus orchard. (Courtesy Race and Race, Inc.)

and advantageous to the small farmer doing his irrigation along with his field work. This low rate of application makes it necessary to move the sprinklers only twice a day on soils with low water-holding capacity.

The portable fixed-head sprinklers illustrated in Fig. 81 are used more extensively in orchards and nurseries and for golf courses. They do not cover such a large area and give higher water application rates. They are particularly valuable in irrigating seedlings that would be damaged by sprinkling unless the spray was fine.

In a few places irrigators are using a canvas hose which is so made that water will seep from the hose throughout its length and percolate into the soil. This type is not very common, owing to small coverage and high cost of installations.

95. Pressures Sprinkler systems operate under a wide range of pressures from 5 psi to over 100 psi. The pressure depends upon power costs, area to be covered, type of sprinkler used with systems, and crop being sprinkled. Low pressures range from 5 to 20 psi; medium from 21 to 50; and high pressures from 51 to 100 psi. Pressures well above 100 psi are designated as "hydraulic." Sprinklers in the low-pressure range have small area of coverage and relatively high sprinkling rates for the recommended spacings of the sprinklers. Their use is generally confined to soils having infiltration rates of more than ½ in. per hr during the irrigation.

Medium-pressure sprinklers cover larger areas and have a wide range of precipitation rates, and water drops are well broken up.

High-pressure sprinklers cover large areas, and precipitation rates for recommended spacings are higher than for the moderate or medium pressures. Moisture patterns are usually good but are easily disrupted by winds.

The hydraulic-pressure sprinklers are usually of the rotating-head reaction type. They have high precipitation rates, above 0.75 in. per hr. The wetted diameter of circle is from 200 to 400 ft. Moisture patterns are very good in calm air but are easily disturbed by winds.

In general, the sprinklers on the market will fit practically any of the operating conditions in the field.

96. Types of Sprinkler Systems The sprinkler system includes the sprinkler, the riser pipe, the lateral distribution pipe, the main line pipe, and, often, the pumping plant. Sprinkler systems are classified as permanent, semipermanent, portable, and fully portable, according to variations in these parts.

There are permanent installations having permanent sprinklers, permanent buried main and lateral pipe lines, and fixed pumping plant. These installations are high in initial cost but low in costs for operation. They are used in orchards, citrus groves, and nurseries. A variation of this system has sprinklers mounted on quick-coupling risers so that they may be moved along the lateral lines. This reduces the number of sprinklers and increases the labor needed for operation of the system.

Semipermanent sprinkler systems consist of buried main pipe lines, portable lateral pipe lines and sprinklers, and fixed pumping plant. This type of sprinkler system is suitable for orchards, permanent pasture, and general crops where the entire farm is to be sprinkled and the field boundaries are fixed.

The portable low-angle sprinkling system, illustrated in Fig. 82,

is made up of portable main pipe line, portable lateral pipe lines and sprinklers, and fixed pumping plant. This system is used to irrigate field crops on a farm having a crop rotation and changing field boundaries.

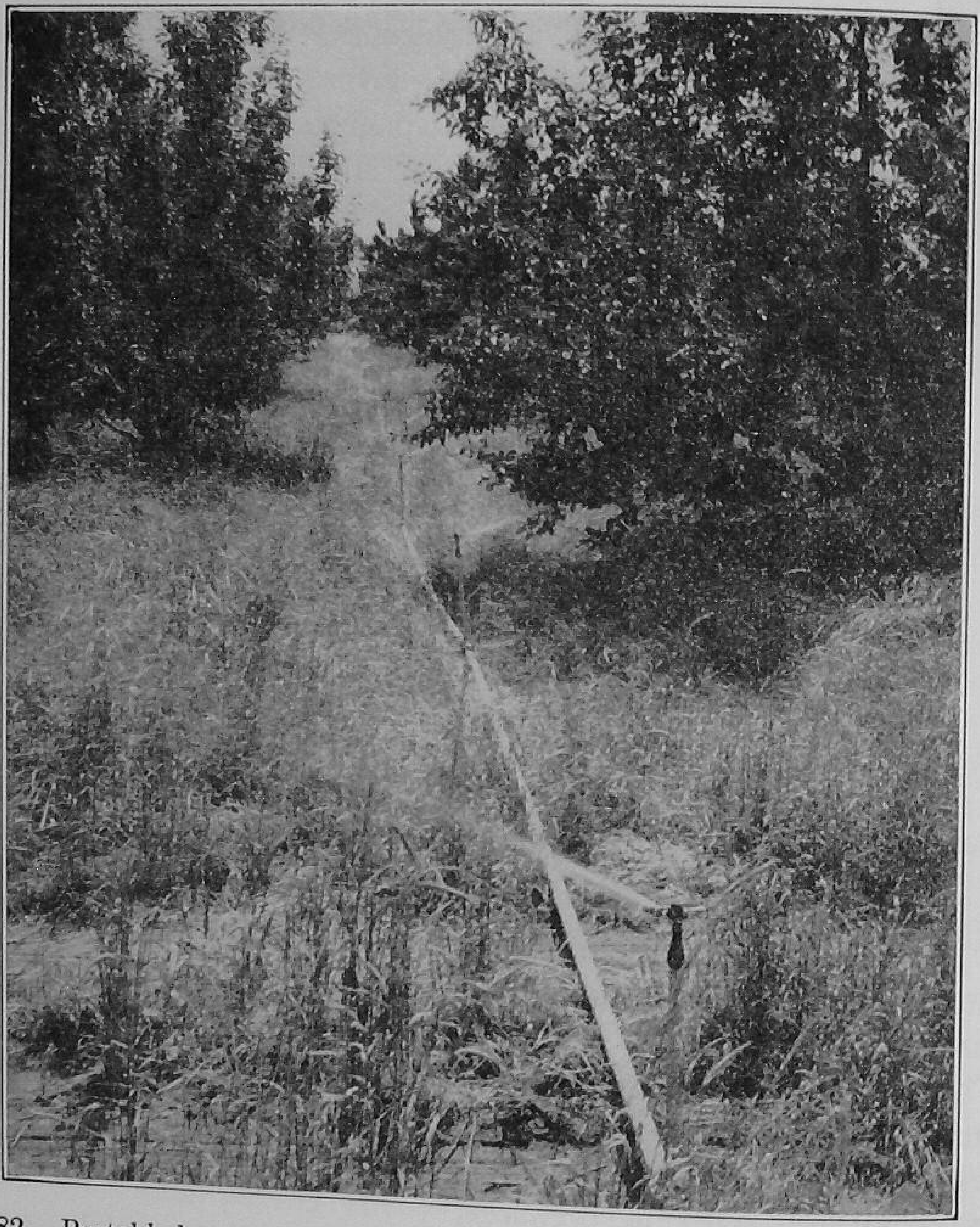


FIG. 82. Portable low-angle sprinkling system for Class IV orchard land. Rate of application is ⅓-in. depth per hr. (Courtesy Soil Conservation Service.)

The fully portable system has portable lateral pipe lines with sprinklers and portable pumping plant. This method is used for irrigating one crop which is in rotation with other crops irrigated by surface methods. Another use made of this system is to establish hay and pasture stands, and to germinate beets and truck crops which are later surface-irrigated.

97. Sources of Water and Methods of Developing Pressure Sprinkler systems require sources of water free of debris that will clog the

sprinklers. The common sources are wells, irrigation canals, rivers, and lakes. The best sources of debris-free water are wells and lakes. Screening boxes are necessary to remove the debris when water is taken from irrigation canals or rivers.

Pressure for operation of sprinklers is obtained from gravity when practical and supplied by pumps when the source of water is located at such a level that gravity pressure will not operate the sprinklers. In some systems, combinations of both sources of obtaining pressure are used.

When pumping from lakes, streams, and irrigation canals, centrifugal pumps are used to develop pressure. When pumping from wells either a centrifugal or turbine pump is used. The turbine pump is better adapted to wells in areas having a variable water table during the irrigation season.

98. Sprinkler System Design Requirements The important factors in the success of sprinkler irrigation systems are first, the correct design, and second, the efficient operation of the designed system. The basic information necessary for the design of a farm irrigation system is obtained from four sources, namely, the soil, the water supply, the crop to be irrigated, and the climate.

Information concerning soils includes the soil type, depth, texture, permeability, and available water-holding capacity of the root zone. Necessary water supply concerns the location of the water delivery point in relation to the fields, the quantity of water available, and the delivery schedule. The maximum consumptive use of water per day, the root-zone depth, and the peculiarities of irrigation necessary to be taken into account in the irrigation system are obtained from a knowledge of the requirements of the crop to be grown. Climatological information includes the natural precipitation and wind velocities and direction. All this information must be compiled in one form or another before starting to design a sprinkler system.

The performance requirements of a sprinkler system include:

1. Design and operation to apply water at a rate that will not cause runoff from the area irrigated during the operation of the sprinkler system.
2. Application of water at such a rate that high water-application efficiency is obtained. The minimum rate is determined by evaporation and interception on the foliage. It varies from area to area.

The sprinkler system must have the capacity to meet the peak water-use demands on each crop during the irrigation season. Allowance in capacity must be made for unavoidable water losses by evaporation, interception, and some deep percolation.

When a system is designed for supplemental irrigation or protective purposes, the system should have a capacity to apply the necessary depth of water to the design area in a specified time. The cost of the system should be consistent with the insurance values involved.

A sprinkler system should not apply more water than the capacity of the soil to hold water for crop use.

There should not be more than a 10 percent variation in the depth of water applied to any part of the design area. This variation can be controlled by maintaining the pressure throughout the system within 20 percent. Variations in pressure occur as the result of friction loss in pipes and elevation changes in main lines or lateral lines. Frequently, it may be necessary to control pressures with valves.

A sprinkler system must apply water so that it will not cause physical damage to the crop. In orchards, high-velocity streams of water from sprinkler nozzles have bruised growing apples when sprinklers have been placed too close to the trees. Also, in crops having fine seedling plants, a fine spray must be applied, or the plants will be beaten into the ground. Such a spray requires high pressures to break up the water drops at the nozzle.

The sprinkler system should be designed to apply water at the lowest annual cost. A balance between pipe size and pumping costs is demanded in a system operated by pumping. Careful analysis should be made to arrive at a reasonable balance between equipment costs and power costs.

When used in practical field spacing with selected operating pressures the sprinkler chosen must give satisfactory moisture distribution.

If a pump is necessary it must be picked on the basis of the maximum operating conditions of head and gallons per minute and must not overload at minimum operating conditions.

99. Operation of Sprinkler Systems A sprinkler system may be well designed for the crop and area, but, if it is not efficiently operated, the results will be disappointing. A correctly designed sprinkler system will supply adequate water during periods of maximum water demand by the crop to give satisfactory production. Over-irrigation will result if the system is operated at full capacity when the water demand by the crop is less than maximum. This over-irrigation will cause soil erosion, leaching of soluble plant food, low water-application efficiencies, reduction in quality and quantity of crops, and, ultimately, a drainage problem.

The operation of sprinkler systems should be governed by the following rules:

(*a*) Check the soil moisture in the root zone with a soil auger or probe to determine when to irrigate.

(*b*) Check depth of water penetration while irrigating to determine when to stop applying water.

(*c*) Check depth of water penetration several days after water has been shut off to see that root-zone soil has adequate moisture.

These rules of operation will insure the highest efficiencies with sprinklers as with other irrigation systems.

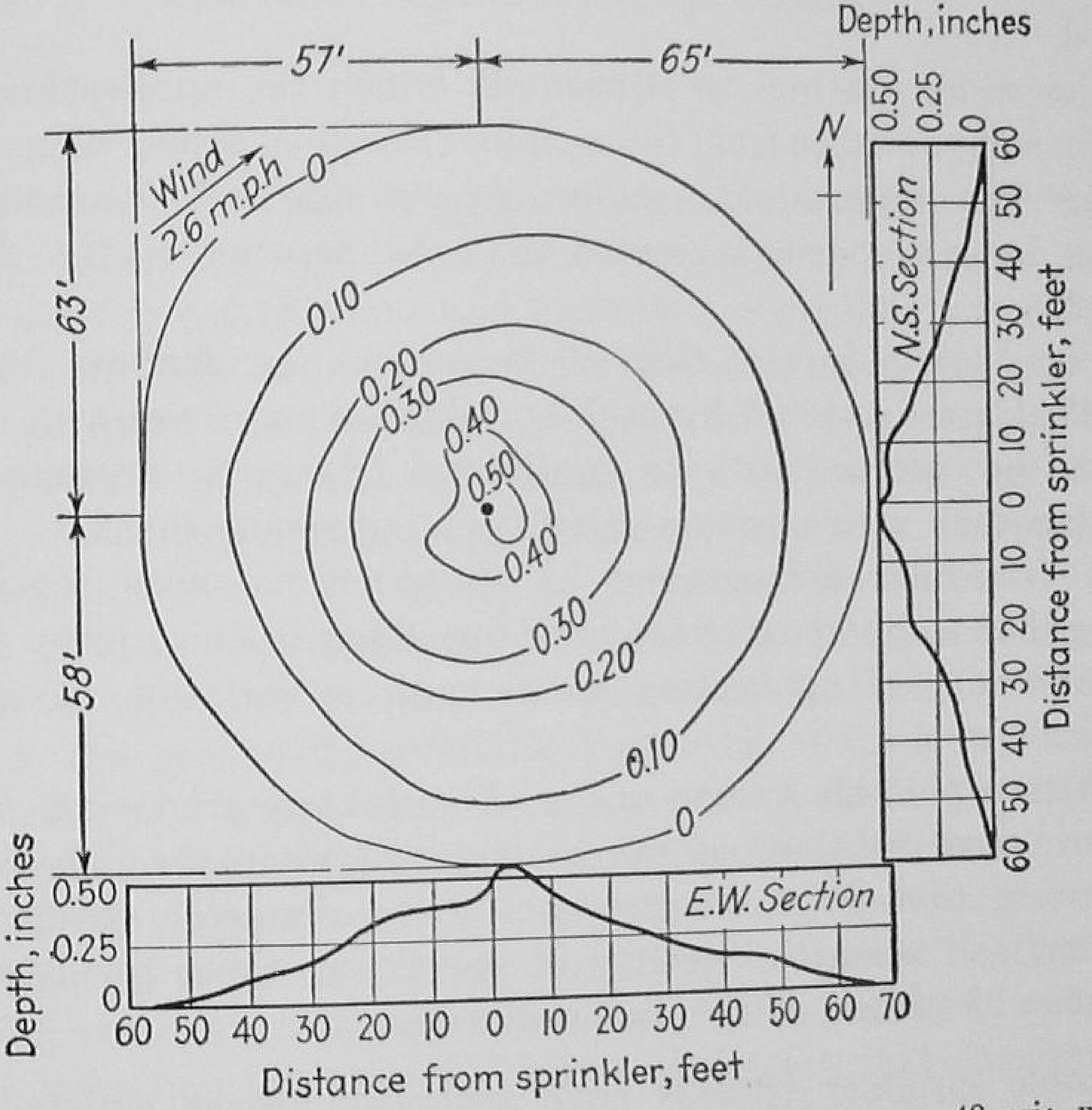


FIG. 83. Sprinkler G-3; nozzles, 1/4 and 7/32 in. under pressure, 40 psi; with discharge of 19.3 gpm. (*Calif. Agr. Exp. Sta. Bul.* 670.)

100. Sprinkler Irrigation Experiments The University of California has conducted extensive and detailed experiments on sprinkling irrigation, reports of which have been prepared by Christiansen.

Many factors influence the efficiency and economy of sprinkling irrigation. One of the important factors is the uniformity of water distribution. Figure 83 shows that the maximum depth of water applied is near the sprinkler and that the depth decreases gradually as the distance from the sprinkler increases.

The following is an interesting summary by Christiansen of important factors in sprinkling irrigation:

1. The uniformity of distribution of water from sprinklers varies greatly, depending upon pressure, wind, rotation of sprinkler, spacing, and many other factors.

2. A nearly uniform application is possible with proper sprinkler patterns and with proper spacing of sprinklers.

3. Sprinkler patterns approximately conical, where a maximum application occurs near the sprinkler and decreases gradually to the edge of the area covered, produce a fairly uniform application when sprinklers are not farther apart than 55 to 60 percent of the diameter covered.

4. For wider spacings, a pattern for which the application is uniform for some distance from the sprinkler and then tapers off gradually, is better; but the maximum uniformity obtainable decreases with the spacing for all spacings greater than 50 percent of the diameter covered.

5. For spacings greater than 50 percent of the diameter and with equivalent areas covered by each sprinkler, a more uniform application can be obtained with an equilateral triangular arrangement of sprinklers than with a square or rectangular arrangement.

6. A triangular arrangement of sprinklers is more sensitive to spacing than a square or rectangular one. That is, for a given pattern, the uniformity of application varies with a variation in sprinkler spacing.

7. With a portable system and with sprinklers producing desirable patterns, good distributions can be obtained when the line is moved not farther than 50 to 70 percent of the diameter covered by a sprinkler, and when the spacing of sprinklers along the line is not more than 35 percent of the diameter covered.

Portable sprinkler systems have generally proved satisfactory in areas with a high water table, and occasionally near the coast where the seasonal water requirement is low. They are satisfactory for irrigating spring crops, such as peas, that require only one or two light applications in addition to the normal winter rainfall. They are especially well adapted to land of irregular topography that is difficult to irrigate by surface methods, and for shallow, coarse-textured, highly permeable soils of low available water capacity that require light applications at frequent intervals. Sprinkling is generally satisfactory for special conditions where surface irrigation is not feasible or practical. It is limited principally by the cost, that, for most conditions, is higher than for surface methods of irrigation.

7
Farm Irrigation Implements and Structures

Extensive use of well-designed modern implements for leveling irrigated lands, making borders, construction and cleaning of ditches, and for making corrugations and furrows is contributing to irrigation advancement. It is essential to efficiency and economy that the lands of each irrigated farm be well prepared for irrigation and also be provided with structures that facilitate easy control and regulation of the irrigation water during its application to the land. Comparatively little attention has been given to irrigation structures by public research agencies, the more basic problems in the relations of irrigation practice to soils and to plants having thus far been given major attention. The greater the available knowledge of the interrelations of soils, plants, and water, and the greater the demand for water, the more urgent it becomes that the irrigator be able to control the stream at his disposal and to spread the water uniformly over the land surface in order to moisten the soil to the desired depth without sustaining excessive losses of water. Some of the modern implements used in irrigation farming and farm structures that facilitate the control of water are described in this chapter.

101. Implements The farm implements of first importance in irrigation are tractors, plows, spike-tooth harrows, disk harrows, scrapers, and levelers. Good plows and good plowing contribute greatly to the possibility of uniformity in distributing irrigation water. Lands that are irrigated by the ordinary flooding methods especially require good plowing because, owing to the lack of specially prepared levees, there is no means of crowding water over the higher land areas of poorly plowed fields. Careless plowing of lands that are to be irrigated by flooding, or plowing with dull, poorly kept plows, is followed by inefficient irrigation.

Fig. 84. Farm tractor and small carryall scraper used for land leveling. The box on the end of the tractor provides more weight on the front wheel, which makes it easier to load the scraper. (Courtesy Soil Conservation Service.)

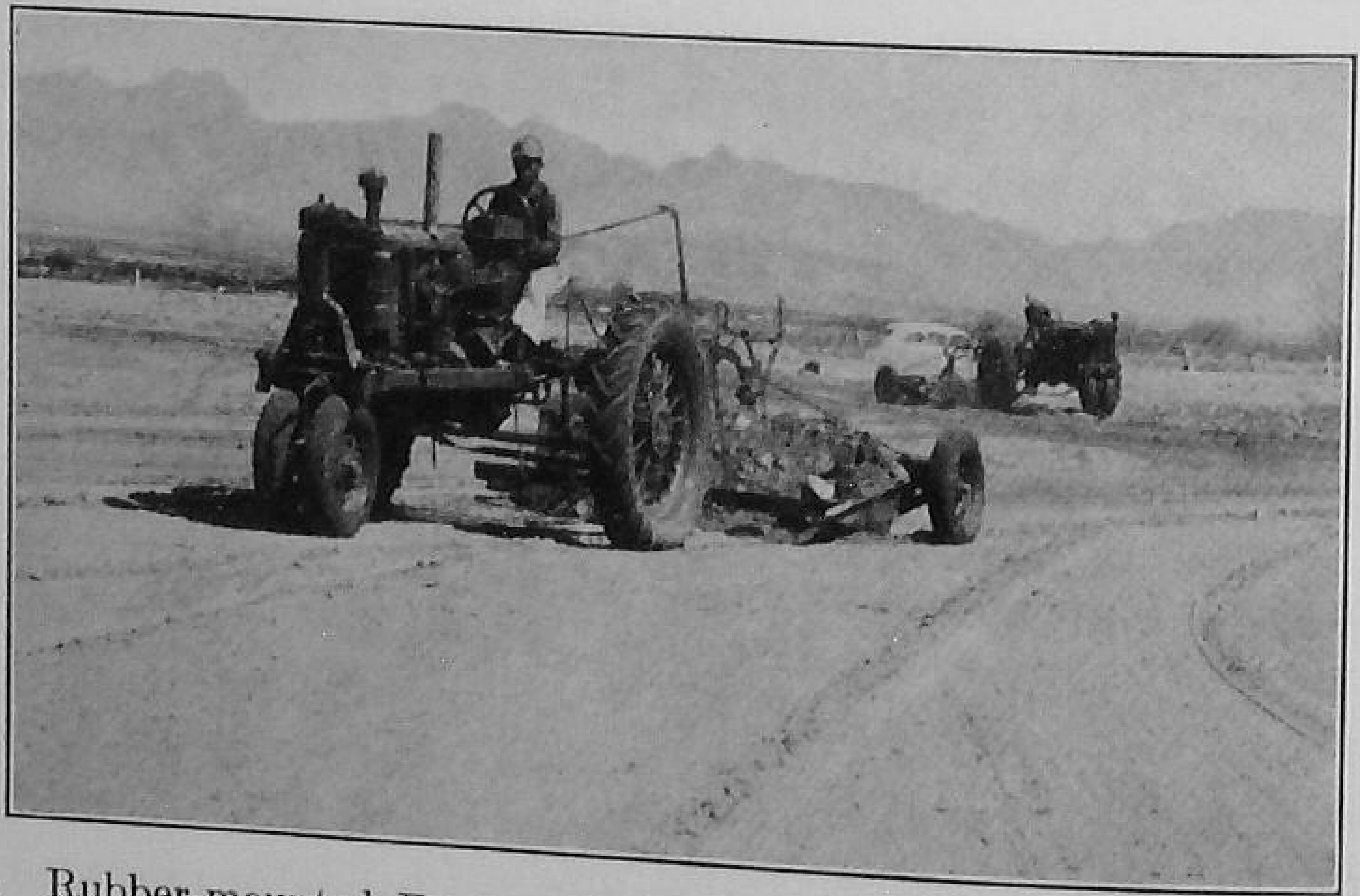


Fig. 85. Rubber-mounted Fresno adapted to moving soil long distances. Final smoothing of land should be done with a drag or float. (Courtesy New Mexico Exp. Sta.)

102. Implements for Leveling Lands Scrapers like the carryall shown in Fig. 84 and the Fresno in Fig. 85, drawn by power tractors, have contributed greatly to advancement in land leveling. After the large cuts and fills are accomplished with the scraper the lands are leveled and smoothed with large automatic levelers like the land plane shown in Fig. 86.

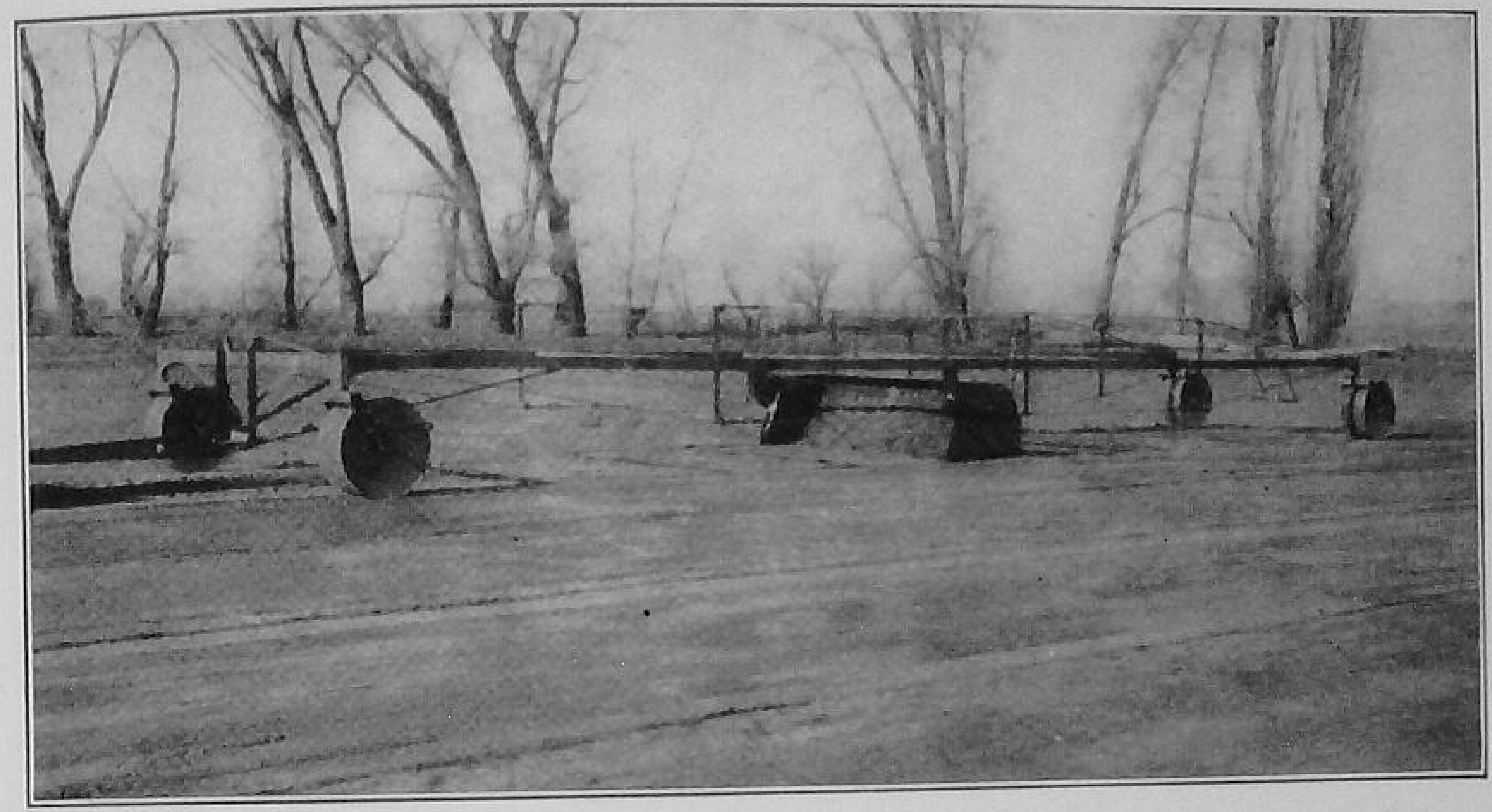


FIG. 86. Land plane for leveling has been found satisfactory by many irrigators. (Courtesy Soil Conservation Service.)

Farmers who depend on the flooding and furrow methods are more and more using modern land leveling and tillage implements in order to obtain a smooth land surface in which there are few, if any, small depressions or elevations.

103. Border-Making Implements In addition to the use of well-built scrapers and other land-leveling implements on the larger farms, special border-making scrapers drawn by tractors have proved to be economical for making borders. For smaller farms adjustable bordering machines like the one developed by Arizona farmers in the Salt River Valley, illustrated in Fig. 87, are very helpful. The frame attached to the rear end of the Arizona implement smooths and grades the top of the levee in the same operation which crowds the soil together to make a levee.

104. Implements for Making and Cleaning Ditches The pioneer methods of digging irrigation ditches with hand labor and the pick and shovel are largely past. Power-drawn ditching machines, illustrated in Fig. 88, have greatly reduced the costs and the time required for construction of canals and ditches. Where ditches with steep banks

Fig. 87. Preparing land for the border method of irrigation. (Courtesy Union Pacific Railroad Company.)

Fig. 88. Ditching machine which excavates and trims ditch leaving it ready to place a lining. (Courtesy Soil Conservation Service.)

are feasible and desired, carry-type scrapers drawn by a tractor, as illustrated in Fig. 89, are efficient and economical. In the construction of new canals as well as in the repairing of old ones it is often advantageous to compact the soils well in order to reduce seepage losses and also to add to the stability of the soil and thus reduce

FIG. 89. Carry-type scraper drawn by track-type tractor; adapted for working in ditches with steep banks and on long hauls. (Courtesy Caterpillar Tractor Company.)

erosion of the bed and the banks of the canal. The sheepsfoot roller, shown in Fig. 90, for many years always used in the construction of earth dams, is now found to be useful also on canals.

A new ditcher designed and constructed in Utah and found to be especially useful for cleaning the banks of canals is illustrated in Fig. 91.

105. Corrugation Implements Shallow furrows are designated as corrugations. Several types of homemade corrugators are used: One, a

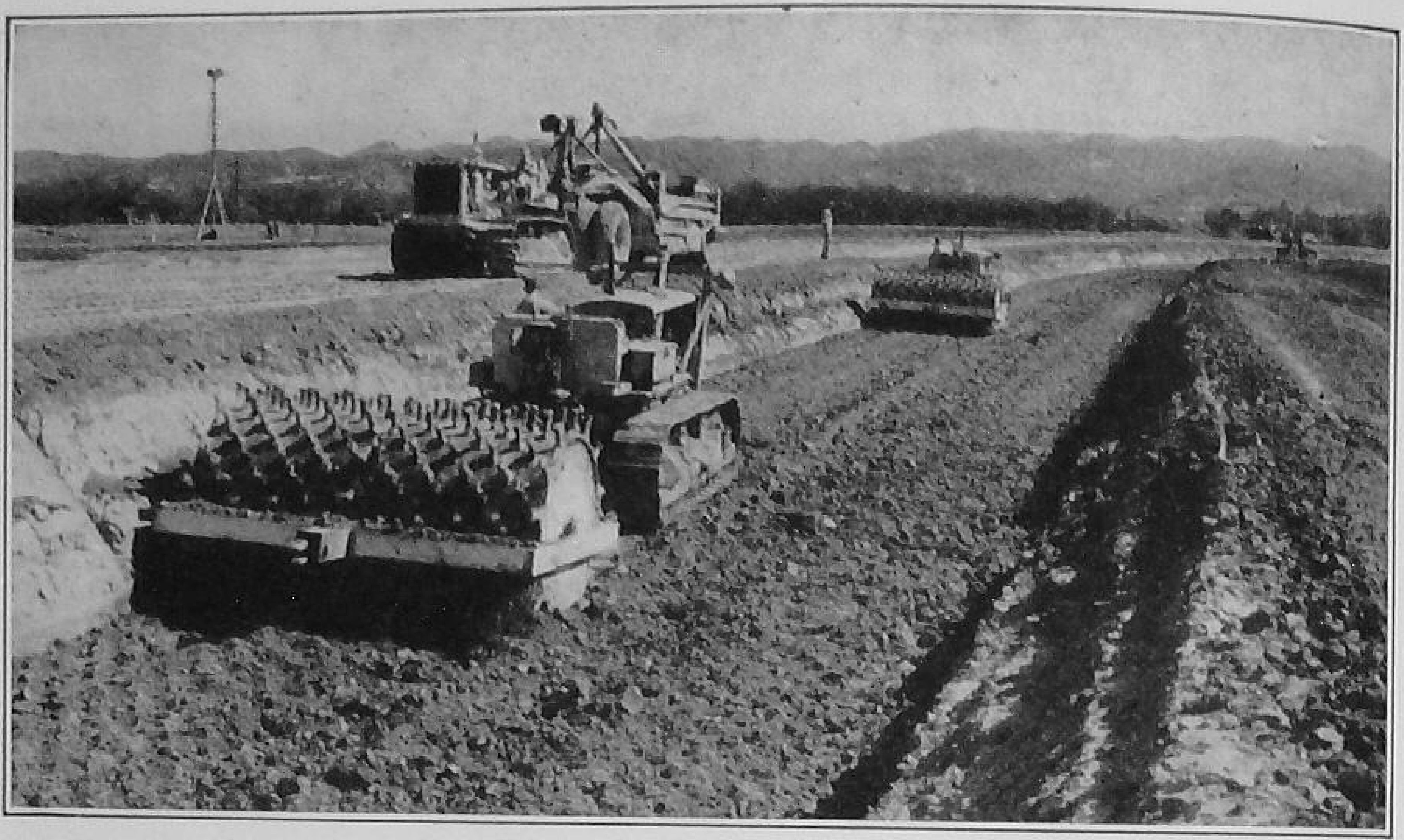


Fig. 90. Heavily weighted sheepsfoot tampers are valuable in ditch construction. Tamping makes the soil resistant to seepage and erosion, and weed growth is retarded. (Courtesy Caterpillar Tractor Company.)

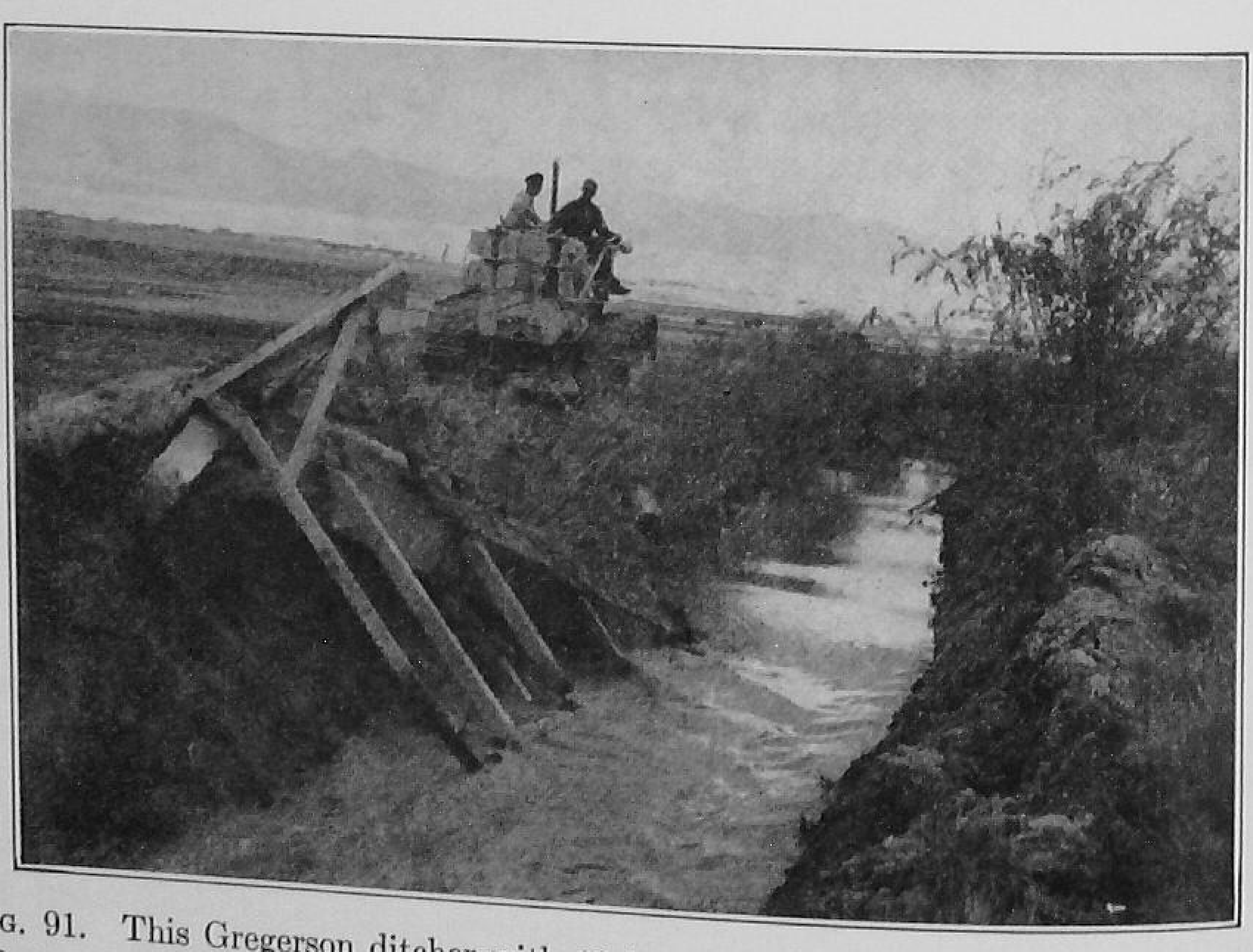


Fig. 91. This Gregerson ditcher with 18-ft blade for clearing canal banks weighs 3.2 tons and will operate in 5-ft-depth ditches having steep banks. (Courtesy Robinson Machinery Company.)

roller around which collars of the desired thickness and depth are built; another, a drag having runners as corrugators. The roller type compresses and compacts the soil as a means of making furrows; the drag type crowds the soil to both sides of the runner. These corrugators are limited in use to newly plowed land. For old alfalfa land, clover land, or other land having a compact surface, heavy, well-constructed steel corrugators are needed to make satisfactory furrows.

106. Deep-Furrow Implements Potatoes, corn, asparagus, celery, and orchards on some soils are best irrigated by using deep furrows, especially in heavy soils. Many orchard crops, such as apples, peaches, lemons, olives, and almonds, are also best irrigated by means of deep furrows. Common shovel plows are sometimes used for making the furrows. For orchard irrigation on land having a steep sidehill slope a standard mole board plow may be used by throwing the soil downhill so as to avoid overflowing of the furrows. A two-way sulky plow saves time in making deep furrows on sidehill land.

107. Farm Irrigation Structures Engineers apply the word *structure* to the large dams, head gates, sluices, flumes, inverted siphons, chutes, and drops which are built to divert water from natural sources and convey it to the farms for irrigation. The devices and pieces of equipment used by the individual irrigator to divert water from a large canal into his ditch and convey it to the several parts of his farm are here designated farm irrigation structures. In some communities rather crude farm irrigation structures are made to suffice even though the labor cost required in the use of such structures is sometimes very high. As a rule, it is economical, and it is always most satisfactory to the irrigator, to build structures that have the required capacity and the strength to control the water. Many irrigation canals in the West, and particularly in the Rocky Mountain states, are built along the rims of the valleys immediately above the irrigated lands so that each irrigator obtains water directly from the main canal which carries water during the entire irrigation season. On such canals satisfactory take-out structures are especially necessary. Farm irrigation structures include two general classes, namely, permanent and temporary structures. No structure is truly permanent, in the strict sense of the word, but the term is applied to those structures which remain in place during one or more irrigation seasons. Temporary structures are those that are moved from place to place during each irrigation, or those that are built for only one season's use. A further desirable classification of structures is based on the function of the structure

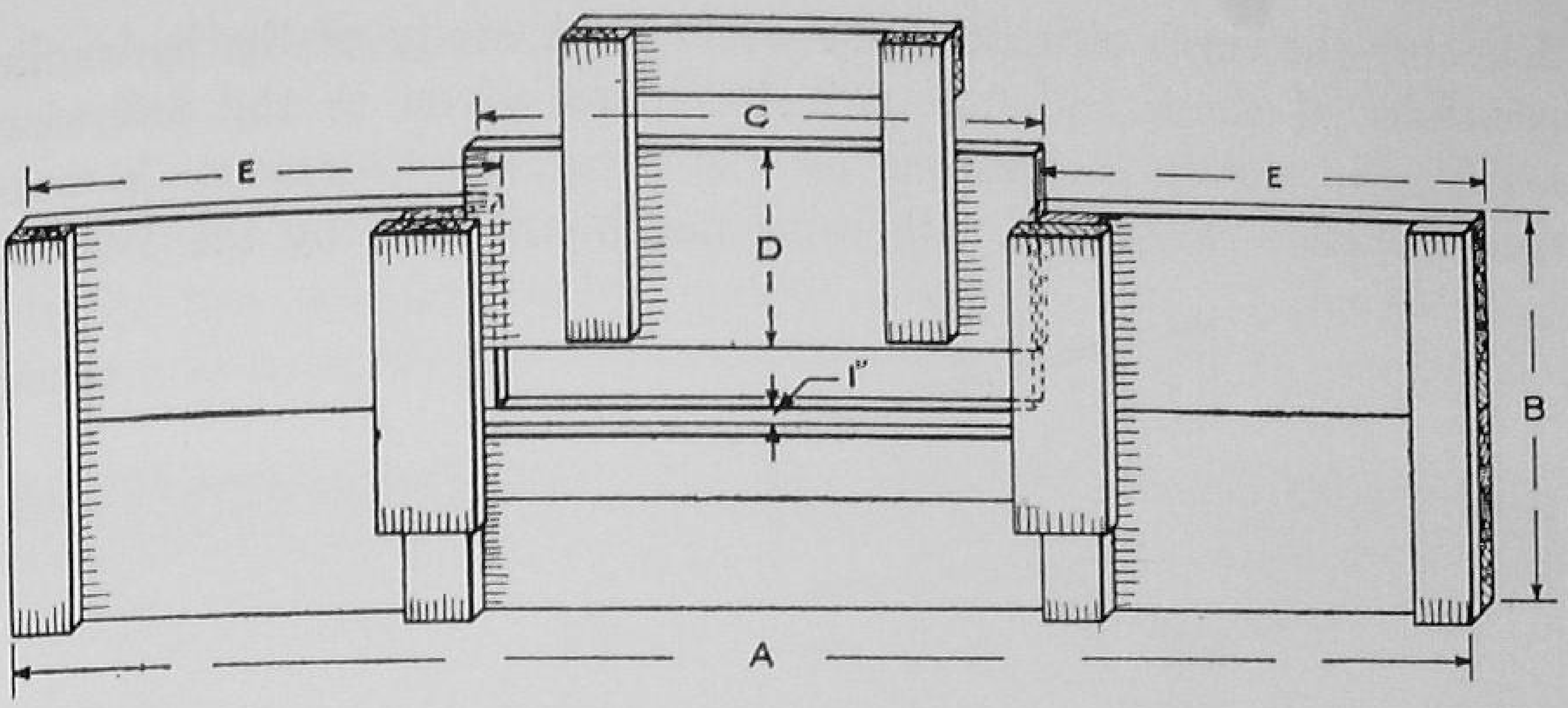
and includes: diversion, conveyance, and distribution structures listed herewith.*

	Permanent	Temporary
Diversion	Check gates Take-out channels Hydrants or valves Tubes Division boxes	Portable steel dams Canvas dams Earth dams Straw and earth dams
Conveyance	Ditches Flumes Surface pipes Underground pipes	Ditches Slip joint pipes Canvas hose
Distribution	Surface pipes Levees Spray pipes Nozzles	Furrows Corrugations Border strips Checks Portable sprinkling pipe system

108. Permanent Diversion Structures There is lack of uniformity in the names applied by different irrigation authorities to the several diversion structures. The author suggests the following designations with the thought that improvements will be made by those interested until well-recognized and standard terms may be agreed upon.

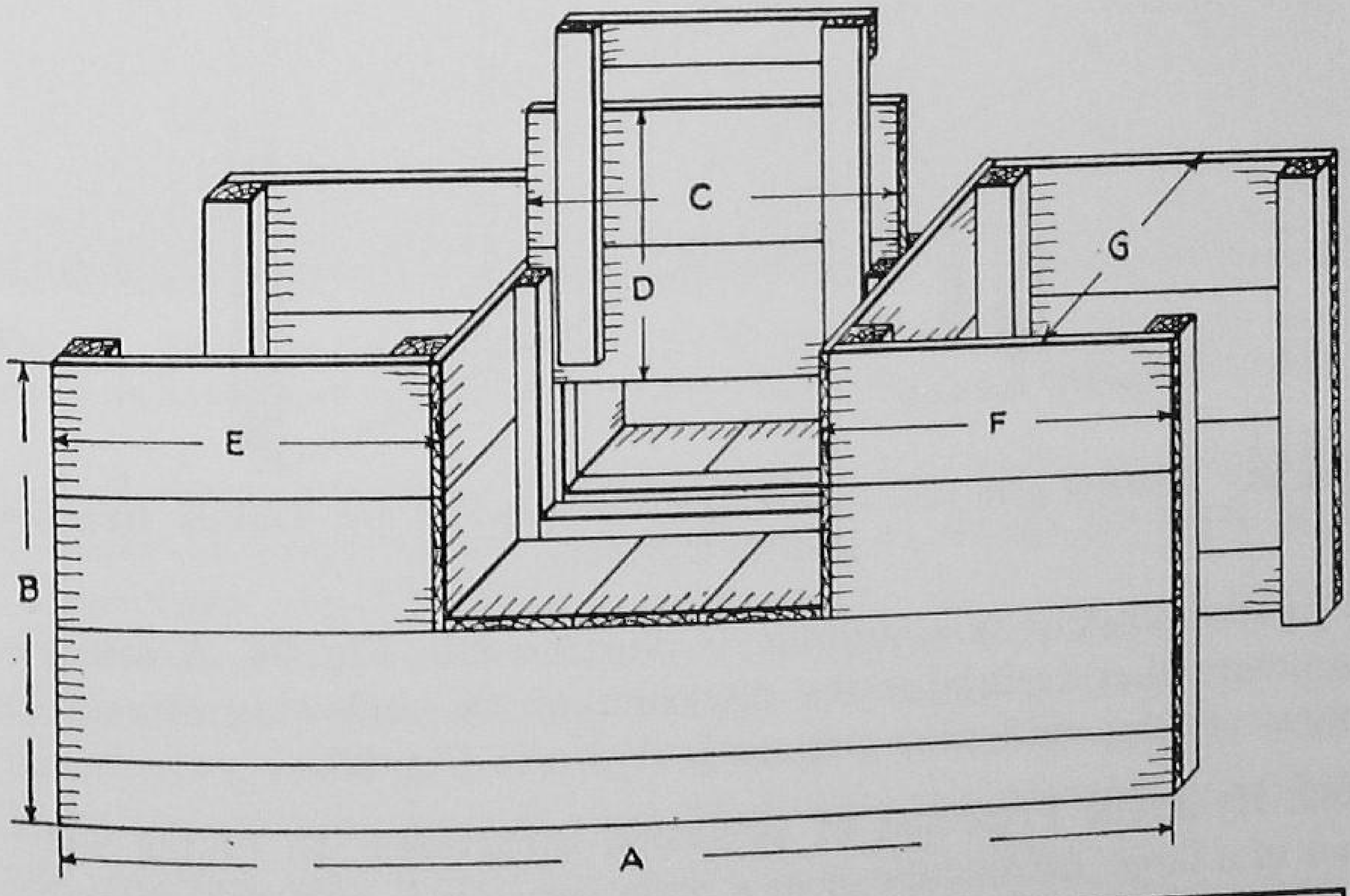
A *check gate* is a gate placed across a stream from which it is desired to divert water. The function of the check gate is analogous to that of the dam or the diversion weir on the rivers at the heads of canal systems. Check gates are built across laterals and ditches for the purpose of diverting part or all of the stream. The *take-out gate* is a part of the farmer's "diversion works" and is analogous to the head gate of the main diversion works on the river system. Its function is to regulate the quantity of water flowing into the small lateral, the field ditch, or the furrow. Typical wooden check gates are illustrated in Figs. 92 and 93. These gates may also be used as take-out gates, although pipe or culvert take-outs are commonly used, especially to take small streams out of large canals. For check gates in large canals in which the quantity of water fluctuates appreciably, it is desirable to place flashboards on the bottom of the stream so that the water which passes the check gate and goes on down the canal is forced to

* Structures for measuring irrigation water and for dividing a stream into different parts are described in Chapter 3. The irrigation devices here classed as "temporary farm irrigation structures" are described by some authorities as "irrigation equipment."



DESIGNED FOR HEADS OF	A	B	C	D	E	LUMBER THICKNESS
1 cfs. - 2 cfs	8'-0"	2'-0"	3'-0"	1'-0"	2'-6"	1"
2 cfs - 5 cfs	9'-0"	3'-6"	3'-0"	2'-0"	3'-0"	1½
5 cfs - 8 cfs	10'-0"	3'-6"	4'-0"	2'-0"	3'-0"	1½

FIG. 92. Standard single-wing wooden check gate. (*U.S.D.A. Farmers' Bul.* 1243.)



DESIGNED FOR HEADS OF	A	B	C	D	E	F	G
3 cfs - 6 c.f.s.	9'-0"	3'-6"	3'-0"	2'-0"	3'-0"	3'-0"	2'-0"
6 cfs. - 10 c.f.s	12'-0"	4'-0"	4'-0"	2'-0"	4'-0"	4'-0"	2'-6"
10 c.f.s - AND UP	14'-0"	4'-0"	5'-0"	2'-0"	4'-6"	4'-6"	2'-6"

FIG. 93. Standard double-wing wooden check gate. (*U.S.D.A. Farmers' Bul.* 1243.)

flow *over* the check structure, not under it. A study of the hydraulic principles of check and take-out structures, given in the following article, will clarify the reasons for the foregoing statement. A well-made concrete check gate with wood flashboard used by the Turlock

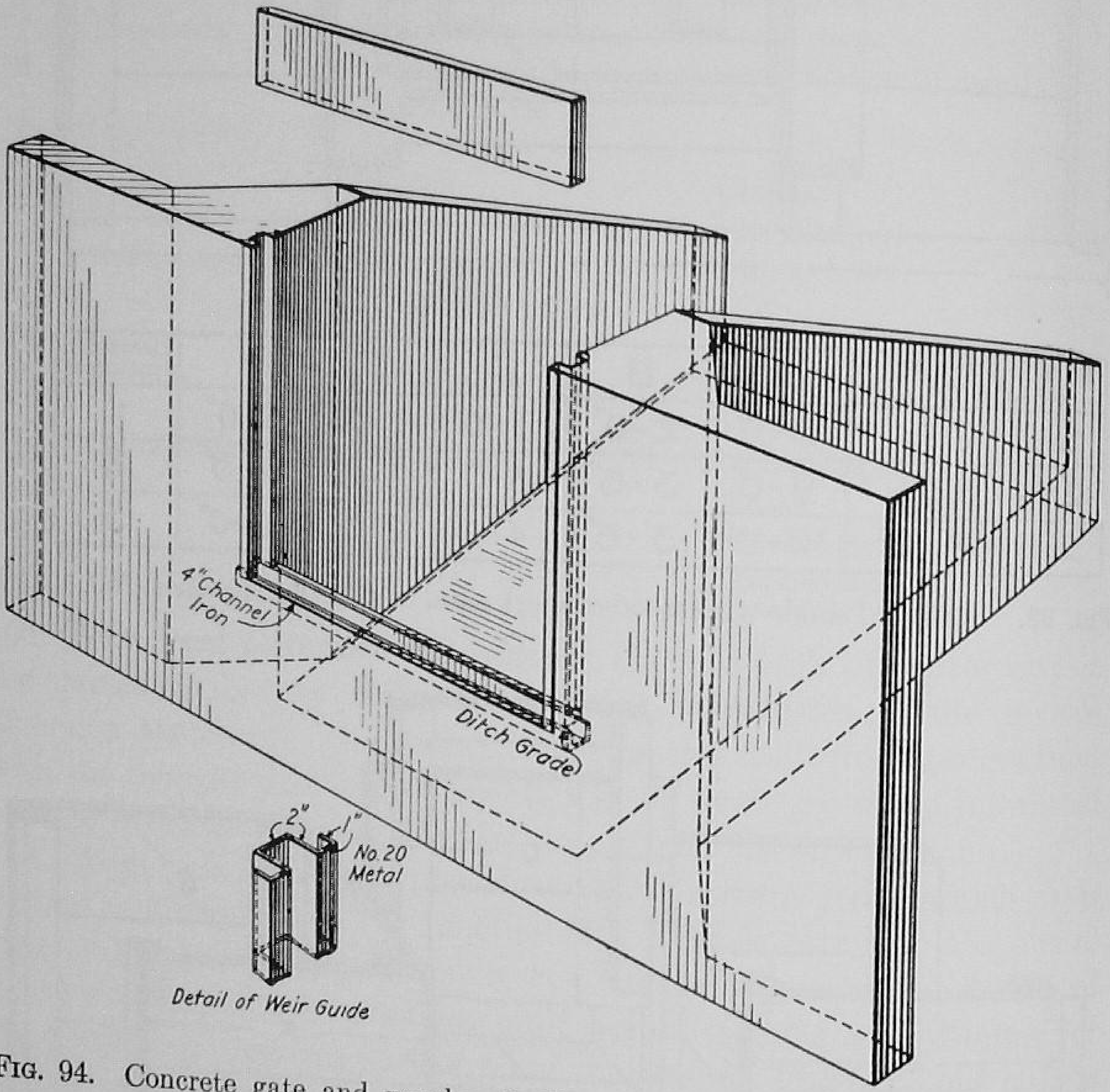


Fig. 94. Concrete gate and wooden flashboard used on the Turlock Irrigation District, California.

Irrigation District of California is illustrated in Fig. 94. A concrete structure that facilitates the diversion of the inflowing stream to either of three outflowing streams is shown in Fig. 95.

109. Hydraulic Principles of Diversion Structures In taking water out of a large distributary or of a main canal, it is as a rule desirable that the farmer obtain a flow as nearly constant as possible. Sudden increases in the quantity of water flowing in the canal, which occur as a result of storms or from closing of take-out gates, should be permitted to flow down the canal with as little obstruction as possible. These two conditions, i.e., approximately constant flow for the irrigator and a minimum of obstruction in the main canal, in general may be

provided by using submerged pipes or culverts as take-outs and overflow flashboards as checks in the main canal to cause the water to rise high enough to submerge the take-out gate and divert the quantity of water the farmer desires. To understand these principles clearly the student should review Chapter 3 on measurement of water and in particular equations 4 and 7. It is seen from equation 7

FIG. 95. Concrete three-way outlet box on irrigation lateral. Water can be diverted to any one or more of the outlets. (Courtesy Soil Conservation Service.)

that H varies with the two-thirds power of q; hence, to double the quantity of water flowing over flashboards as checks, the depth need be increased only 1.59 times.

Equation 4 shows that h varies with the square of q; hence to double the quantity of water flowing through a submerged culvert take-out the effective head, h, must be increased 4 times the original head. Therefore, streams through submerged take-outs are subject to much less variation than those through overpour take-outs.

110. Temporary Diversion Structures In order to divert water from the small ditches on the farm many irrigators use only temporary earth dams. They make each dam at the time and place desired by means of an ordinary shovel. In some soils that erode easily it is helpful to use a little partly rotted straw or weeds temporarily held in place by means of wooden stakes driven into the soil at the bottom of the

ditch. Temporary earth dams are unsuited to streams of more than 2 cfs and in some soils are very difficult to maintain with a stream of 1 cfs or more.

The labor requirement of temporary dams is greatly reduced by using portable dams of either steel or canvas. Steel and canvas portable dams are illustrated in Figs. 96 and 97. Portable steel dams

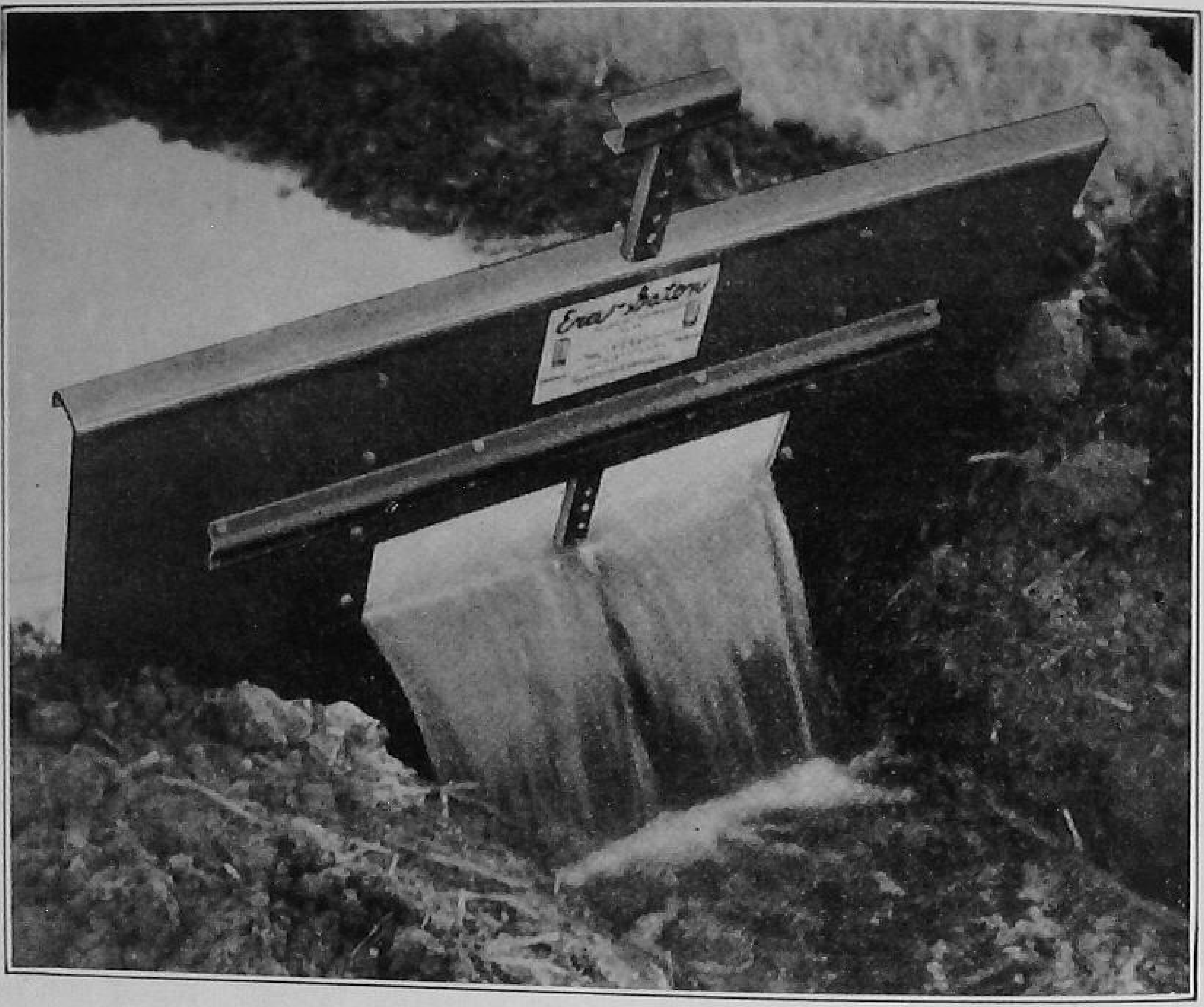


FIG. 96. Era-Gator portable irrigation control gate. (Courtesy Page Metal Products Corporation.)

are suited to streams smaller than those diverted by canvas dams. For streams of 5 cfs or more the steel dam required may be so large as to become burdensome to move or carry about the field. Well-built canvas dams are used to divert streams as large as 8 cfs or more, although streams of 2 to 3 cfs are more commonly diverted by using dams of 12-oz canvas only 5 ft by 6 ft which are easily moved. A heavy, durable, closely woven canvas is necessary to stand the water pressure and prevent excessive leaking.

111. Water-Conveyance Structures The term structure as used herein applies quite as fully to ditches, levees, etc., which are made of earth as it does to devices built of wood, concrete, or metal. Most of the water-conveyance structures in the West are made of earth. The quantity of water that earth ditches will convey may be estimated

from the equations and the tables of Chapter 4. Also the quantities that may be conveyed in flumes and pipes may be estimated from the information and illustrations of Chapter 4.

Conveyance of water under pressure through underground concrete pipe to various points on the farm is becoming increasingly popular, especially in the irrigation of orchards.

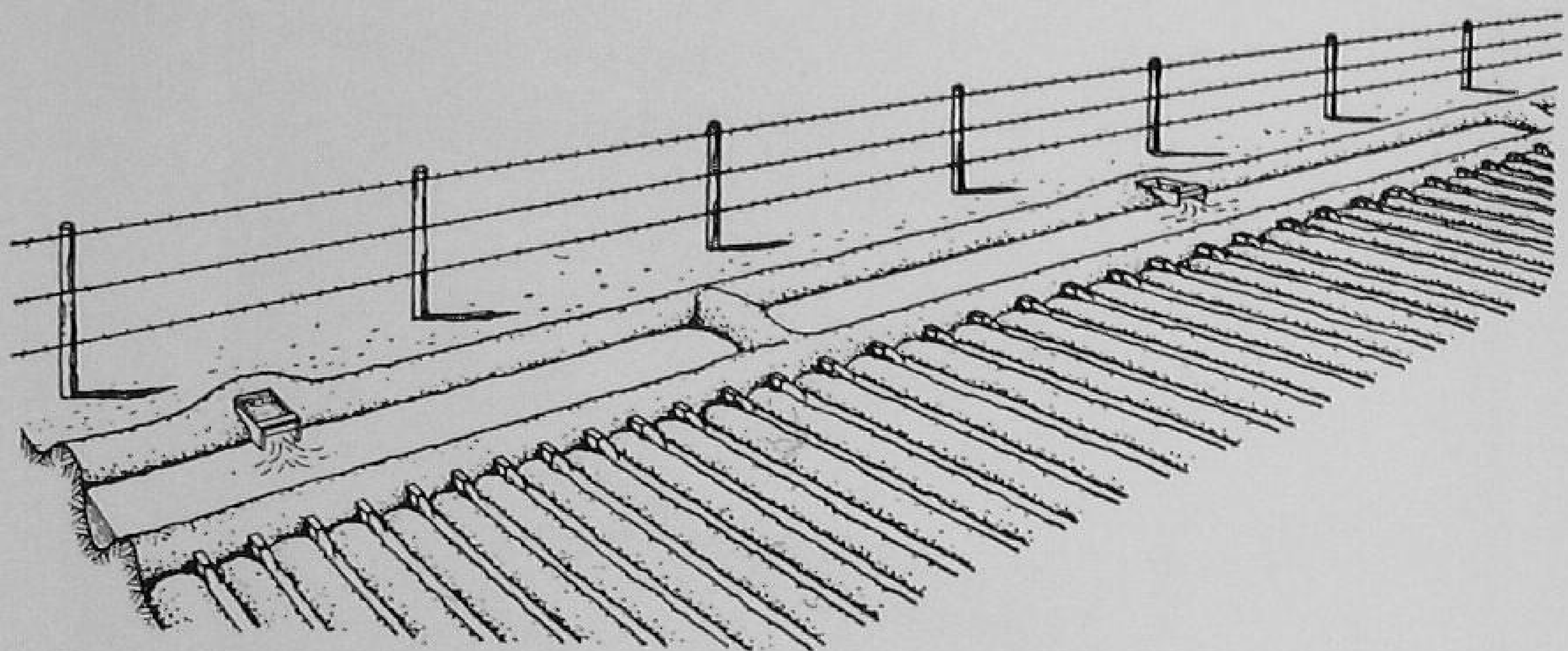
Fig. 97. Eagle ready-to-use irrigation dam in the ditch. (Courtesy Wenzel Eagle Irrigation Dams.)

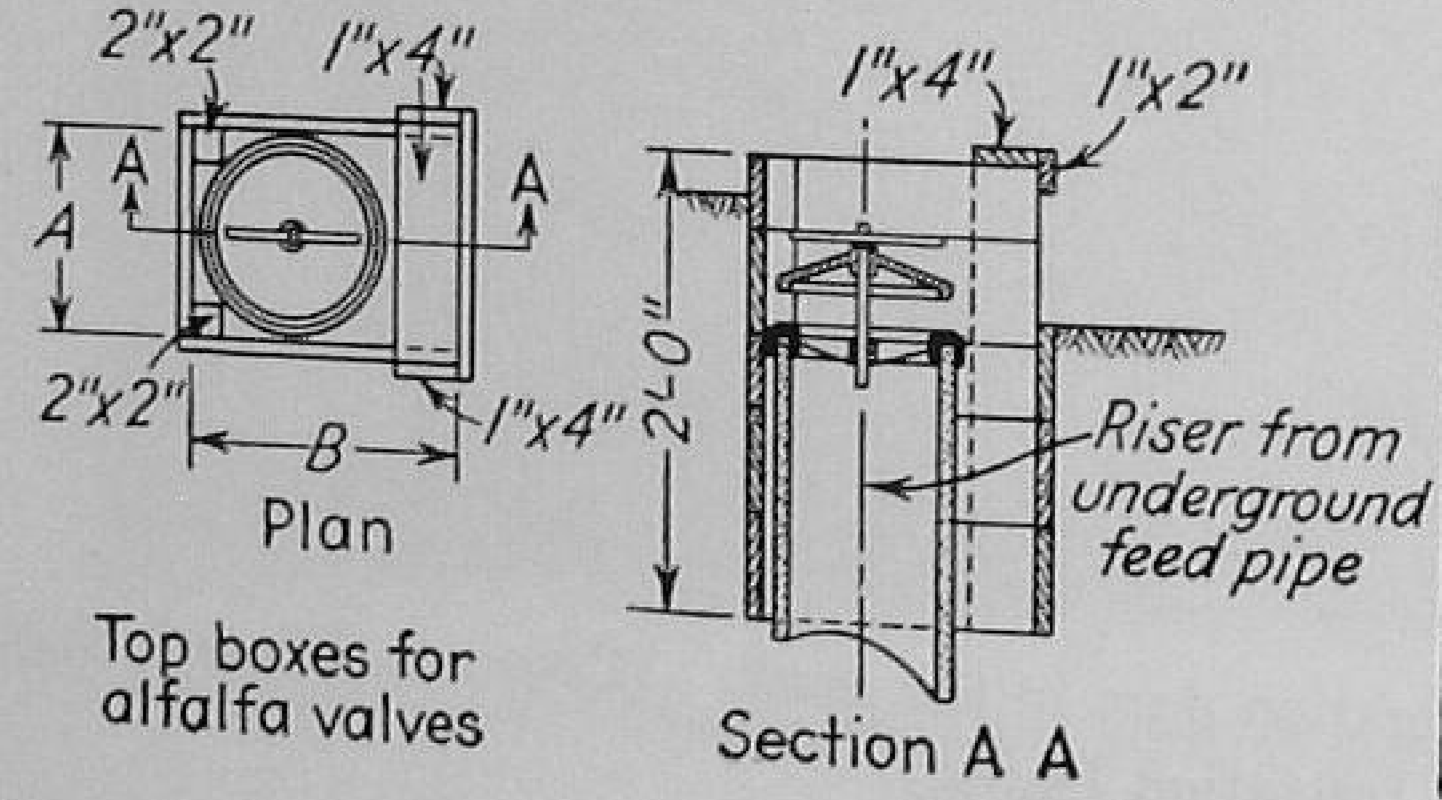
Under the ordinary flooding method of irrigation of perennial crops such as alfalfa and orchards, nearly all the ditches are built more or less permanently. Grain crops, notably wheat, oats, and barley, usually require temporary ditches which are made with an ordinary plow along the higher parts or ridges of the field.

The irrigation farmer is especially concerned with the smaller permanent ditches that convey water to the several farms. These ditches are constructed with plows and with small ditching machines drawn by traction engines. It is customary and usually convenient to build farm irrigation ditches along property lines even though the land slopes along the property lines vary rather widely. On excessive slopes caution must be exercised against erosion of farm ditches, and on small slopes it is important to guard against growth of weeds and grasses in order to maintain a satisfactory discharge capacity.

112. Distribution Structures The use of levees, deep furrows, and corrugations as means of distributing the water over the land surface is described in Chapter 6. Also brief attention is there given to portable sprinkling irrigation systems.

Where land surfaces are very irregular, infiltration rates high, and water expensive, water is sometimes distributed by portable surface pipes. Portable pipes are made of canvas, ordinarily called canvas hose, and of galvanized iron.





Box dimensions schedule

Size of riser	Box dimensions A	Box dimensions B
8"	11"	15"
10"	13"	17"
12"	16"	20"
14"	18"	24"
16"	20"	26"

FIG. 98. Supplying water to ditches by use of orchard and alfalfa valves on underground pipe system. Portable top boxes used to control erosion around valves on sandy soil, and to direct flow of water into irrigation ditches.

The use of slip-joint pipe for distribution is limited to comparatively small areas in only a few irrigated regions. It is not recommended for large farms, and indeed it is uncommon in the intermountain irrigation states. On farms that are somewhat irregular in topographic conditions, and on which only small streams of water are available, slip-joint pipe with which to distribute the water increases the efficiency of water application.

113. Concrete Pipe Underground In California, Oregon, and Washington, and in parts of the mountain states, as well as in Arizona and New Mexico, irrigators are relying on concrete pipe more and more

for distributing irrigation water. Thousands of miles of underground concrete pipe are used in the West.

From the underground concrete pipe water flows upward through riser pipes, and through "alfalfa" or "orchard" valves to an irrigation ditch, a check, or a basin. To prevent erosion of the soil around the riser pipe, top boxes of concrete or wood are used, as shown in Section *A–A* of Fig. 98. Box dimensions for risers of different diameters

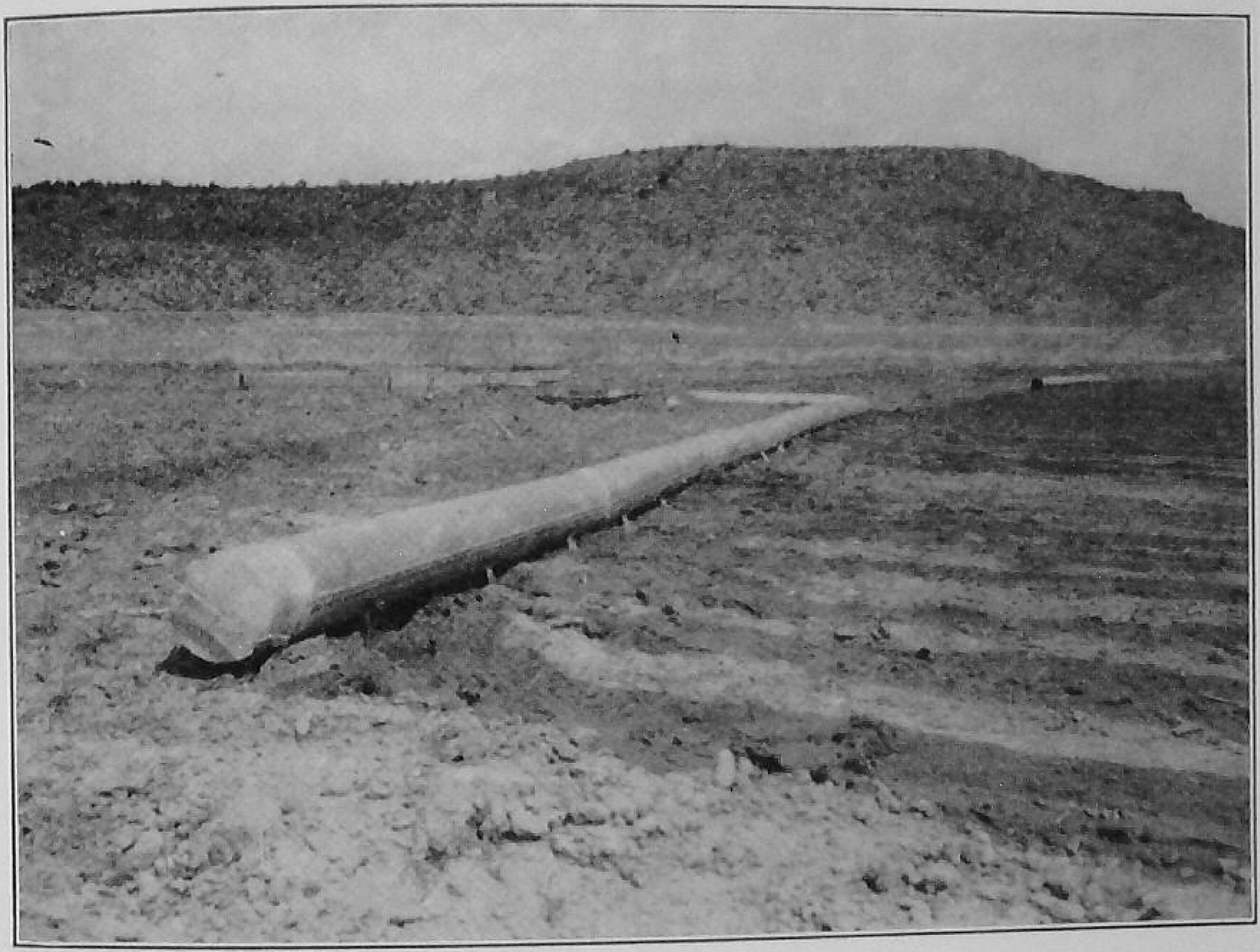


FIG. 99. Fourteen furrows are being supplied controlled streams by this lock-seam gated pipe. (Courtesy New Mexico State College.)

are listed there. Water flows from the concrete pipe riser into the earth distribution ditch. Lightweight cellulose or metal pipe sections about 3 ft long and ranging from 1 in. to 2 in. or more in diameter are placed on the ditch bank to convey water from the ditch to the furrow. Some farmers prefer tubes made of lath. The use of aluminum lock-seam gated surface irrigation pipe is growing substantially.

Lightweight surface gated pipe, mentioned in Chapter 6, is sometimes used with underground concrete pipe and connected to the concrete riser pipe, thus at once solving the soil-erosion problem around the riser outlet and providing for complete control of the quantity of water flowing into each furrow. Figure 99 illustrates use of this pipe with surface water supply in New Mexico. The convenience of the water control, and the ease of regulating the quantity that is delivered to each

furrow from the underground pipe, are also illustrated in Fig. 100, showing the owner of a Washington farm operating a valve to assure the best flow to the furrow.

114. Costs of Various Methods and Structures The first cost of preparing land for irrigation and of purchasing the required irrigation structures ranges from a few dollars up to $400 or more per acre.

FIG. 100. A Washington farm owner operating a valve to release water from underground concrete pipe for irrigation of his orchard by the furrow method. (Courtesy Bureau of Reclamation.)

Preparation for irrigation by the primitive flooding method requires the smallest financial outlay, whereas preparation for artificial subirrigation or for sprinkling requires the largest investment. It is estimated that the total cost of properly preparing all the irrigated land of the West for efficient application of water will equal approximately the total cost of dams, canals, head gates, and other major irrigation structures required to make water available to the farms. There is still very great opportunity for improving the preparation of land by smoothing and leveling it, and by selecting widths and lengths of border strips; areas of different kinds of checks; length, spacing, and

depth of furrows better suited to soil conditions and irrigation streams. The opportunity for developing improved and modern irrigation structures is also substantial.

Preparation for the border strip or check flooding ranges in cost from $25 to $50 or more per acre; basin preparation, other things being equal, is somewhat more costly.

In providing for irrigation by the sprinkling method, the first cost usually includes the cost of the water supply and therefore is relatively greater than, and not directly comparable to, the costs of preparing land for irrigation by the other methods. For sprinkling systems the cost of the sprinkler pipe, pump, and motor ranges from $50 to $400 or more per acre, and the annual costs, including power, from $40 to $60 or more per acre.

8
Basic Soil and Water Relations

Knowledge of soil and water relations is valuable to watermasters, canal riders, and irrigation company officers, all of whom have the opportunity to improve irrigation practices. Such knowledge is also of value to irrigators who desire to obtain the best possible use of the water available for their farms.

The chief source of all mineral soils is rock, although some limited areas of soils are formed largely from organic matter. The breaking down of rocks into the fine particles which form soils is a result of mechanical disintegration and chemical decomposition.

Chapters 8 to 12 inclusive are devoted to a consideration of the relations of soils and water, with special reference to their influence on irrigation and drainage practices. Soil and water relations of special importance in irrigated regions include the capacities of well-drained soils in the field to retain water available for plants, and the flow, or movement, of water in soils. The salinity and alkali conditions together with translocation and concentration of soluble salts due to the movement and evaporation of soil water also constitute important soil and water relations. Chapter 8 is devoted to definitions and explanations of soil properties and basic soil-water relations, and Chapters 9 to 12 concern the storage and flow of water in soils, together with the salinity and alkali problems, and drainage methods.

115. Soil Moisture Functions and Contents The functions of soil moisture in plant growth are very important. Excessive volumes of water in soils retard or inhibit plant growth and make drainage essential. Sterility of arid-region soils is usually caused by deficient amounts of water. Irrigation is an artificial means of preventing deficiencies in the moisture content of soils. Intelligent irrigation practices, based on knowledge of soil-moisture relations, is also a means of preventing, or at least retarding, the occurrence of waterlogging of soils. Students of irrigation are interested in the basic physical laws that influence the

distribution, storage, flow, and consumptive use of water in unsaturated soils.

Intermolecular forces and tensions in unsaturated soils are influenced by soil texture and structure. These forces give rise to "capillary phenomena" in unsaturated soils which are of special interest in the study of soil and water relations. The close contact of soil particles and the particles having thin water films results in attractive forces of large magnitude.

The forms of water in unsaturated soils and methods of measuring soil-moisture contents are considered in Chapter 9.

116. Sources of Information on Soil Water Contributions to knowledge of soil and water relations in the United States have been made by agronomists, engineers, physicists, and soil scientists. Selected references to some of the bulletins of the United States Department of Agriculture and the agricultural experiment stations of the 17 western states, and to a few of the many articles in *Agricultural Engineering, Journal of Agronomy, Soil Science*, and *Proceedings of the Soil Science Society of America*, are presented in the references for Chapters 8 to 12.

117. Soil and Water Relation Quantities, Symbols, and Units Student progress toward understanding publications from many different sources on soil and water relations is dependent on careful attention to symbols, definitions, equations, and physical dimensions of related soil and water quantities. In the study of the equations of Chapters 8 and 9, which concern largely the static relations of soil water, and also the equations of Chapter 10, which deal with the flow of water in soils, the student should find it helpful to refer frequently to Table QR, p. 21. Study of the symbols in column 2, the engineering units in column 3, and the physical dimensions of the quantities in terms of force, length, and time will be helpful. Reference to Table QR will facilitate student progress in the study of Chapters 8 to 12 and the related technical literature.

118. Soil Texture The mineral particles of the soil are classified according to size into three principal groups, which are called sand, silt, and clay. The particle sizes in each of the groups range between certain limits, which have been fixed at diameters of 2 to 0.06 mm for sand, 0.06 to 0.002 mm for silt, and less than 0.002 mm for clay. Sand grains feel gritty to the fingers and can be distinguished without difficulty by the unaided eye. Silt, barely visible to the naked eye, has the appearance and feel of flour. The individual particles of the clay fraction, many of which are inorganic colloids, are not distinguishable

by the eye, and a large proportion of them are too small to be seen under a microscope. It is this fraction that makes soils swell and become sticky when wet, and shrink and become brittle on drying.

Where the main soil-forming process is due to mechanical disintegration, relatively coarse-grained particles are found. The size of the particles is designated by the word *texture*. Sandy soils are classed as coarse-textured, loam soils as medium-textured, and clay soils as fine-textured. The texture of a soil has a very important influence on the flow of soil water, the circulation of air, and the rate of chemical transformations which are of importance to plant life. The farmer is unable to modify the texture of his soil by any practical means. The size of the soil particles has a great influence on crop production the world over, but to the irrigation farmer it is particularly important because it determines in a large measure the depth of water he can store in a given depth of soil.

To assist students of irrigation in the study of the classification of soils based on texture, the following Soil Conservation Service definitions of 11 classes of soil showing the percentages by weight of the sand, silt, and clay in each class are presented:

Textural Designations

1. Sands	Soil material containing 0 to 10 percent silt plus clay.
2. Loamy sands	Soil material containing 10 to 20 percent silt plus clay.
3. Sandy loams	Soil material having 0 to 27 percent clay and 55 to 80 percent sand; also, soils having 0 to 10 percent clay, less than 50 percent silt, and less than 55 percent sand.
4. Loams	Soil material having 10 to 27 percent clay, less than 50 percent silt, and less than 55 percent sand.
5. Silt loams	Soil material having 0 to 27 percent clay and 50 percent or more silt.
6. Sandy clay loams	Soil material having 27 to 40 percent clay and more than 45 percent sand.
7. Clay loams	Soil material having 27 to 40 percent clay, and 20 to 45 percent sand.
8. Silty clay loams	Soil material having 27 to 40 percent clay, and 20 percent or less of sand.
9. Sandy clays	Soil material having 40 to 60 percent clay and 40 to 60 percent sand.
10. Clays	Soil material having 40 percent or more of clay, 40 percent or less of sand, and 40 percent or less of silt.
11. Silty clays	Soil material having 40 percent or more of clay, and 40 percent or more of silt.

119. Soil Structure Soils in which the particles are relatively uniform in size have comparatively large spaces between the particles, whereas those soils in which the size of the grains varies greatly may become more closely packed and thus the volume of spaces between the grains is restricted. The finer-grained irrigated soils, if properly managed, function as granules, each consisting of many soil particles, whereas, in the coarser-textured soils, each particle functions separately. The existence of granules assures a desirable soil structure. Excessive irrigation, and plowing or otherwise working fine-textured soils when wet, tends to break down these granules. A soil so treated is said to be puddled, and it has a poor structure. Favorable structure in fine-textured soils is essential to the satisfactory movement of water and air.

Favorable soil structure is recognized by soil scientists as the key to soil fertility. Adequate amounts of chemical nutrients in soils, though essential to crop production, do not assure satisfactory plant growth and crop yields. The permeability of soils to water and air, provided by favorable soil structure, are equally as important to crop growth as are adequate supplies of nutrients.

120. Real Specific Gravity The real specific gravity of a soil is a dimensionless quantity and is defined as the ratio of the weight of a single soil particle to the weight of a volume of water equal in volume to the particle of soil. The specific gravity of the common soil-forming minerals varies from 2.5 to more than 5.0. A few minerals, such as quartz and feldspar, usually make up the bulk of the soil. The real specific gravity of the soils which have a low percentage of organic matter varies but little, and approaches closely an average of 2.7, which is the specific gravity of quartz. Some irrigated soils, which are formed largely of organic matter, have a real specific gravity of 1.5 to 2.0, depending on the amount of mineral matter present.

121. Apparent Specific Gravity The apparent specific gravity of a soil is defined as the ratio of the weight of a given volume of dry soil, air space included, to the weight of an equal volume of water. This ratio is known also as the "volume weight" of the soil. The apparent specific gravity is influenced by the structure, i.e., the arrangement of soil particles, and by the texture and compactness. Apparent specific gravity is a soil property of great importance to the irrigation farmer, as will be shown more fully in connection with a consideration of the capacity of soils to retain irrigation water.

Compacting a soil of fixed real specific gravity will increase the apparent gravity because it reduces the space between the soil particles

and thereby reduces the volume of the pore space. When working with irrigated soils, it is necessary to know the apparent specific gravity in order to account for the water applied in irrigation, since it is impractical to measure, by direct means, the volume of water which exists in the form of soil moisture in a given volume of soil. It is necessary to measure the weight of water in a given weight of soil by observing the loss of weight in drying, and then convert the weight percentage thus obtained to a volume percentage by use of the apparent specific gravity;* thus the volume of water in a given volume of soil may be determined. The apparent specific gravity should be known for the soil in its natural condition.

Measurements of the apparent specific gravity of several different classes of soil in their natural condition in the Sacramento Valley, California, gave results as follows:

Class of Soil	Apparent Specific Gravity
Silt-loam soils having fine sandy loam subsoils	1.15
Silt-loam soils	1.31
Clay-loam soils	1.35
Clay soils	1.69

The influence of these different apparent specific gravities of soil on pore space is considered in connection with a discussion of the water capacity of soils in Chapter 9.

122. Pore Space The volume of a 1-in. diameter marble is 0.524 cu in. If the marble is placed in a cubical box having a capacity of 1 cu in. there will remain an air space of 0.476 cu in., or 47.6 percent of the total volume. The same air space will be left by any number of marbles of any diameter if arranged in vertical columns as shown at the left in Fig. 101. If, however, the marbles are arranged in oblique order as shown at the right, there will remain only 25.9 percent air space. These facts show that considerable variation of pore space between spherical particles may result from change in arrangement, but they do not show the maximum range of variation that may occur in the soil. There is great variation in the size and the shape of soil particles, and these differences in particles influence the closeness of contact and the interpacking of small particles between large ones, thus determining the total percent pore space, which for convenience is represented by the symbol S. In general, the coarse-textured, gravelly, and sandy soils have a smaller percentage of total pore space and the fine-textured clay loams and clays have a greater percentage. It is

*See equation 34, Chapter 9.

not unusual in irrigated soils for the pore space to vary from 30 percent up to 60 percent. Some clay soils, contrary to the general rule, are very compact. Certain fine-textured soils in the Sacramento Valley, California, have only 36 percent pore space. To compute the

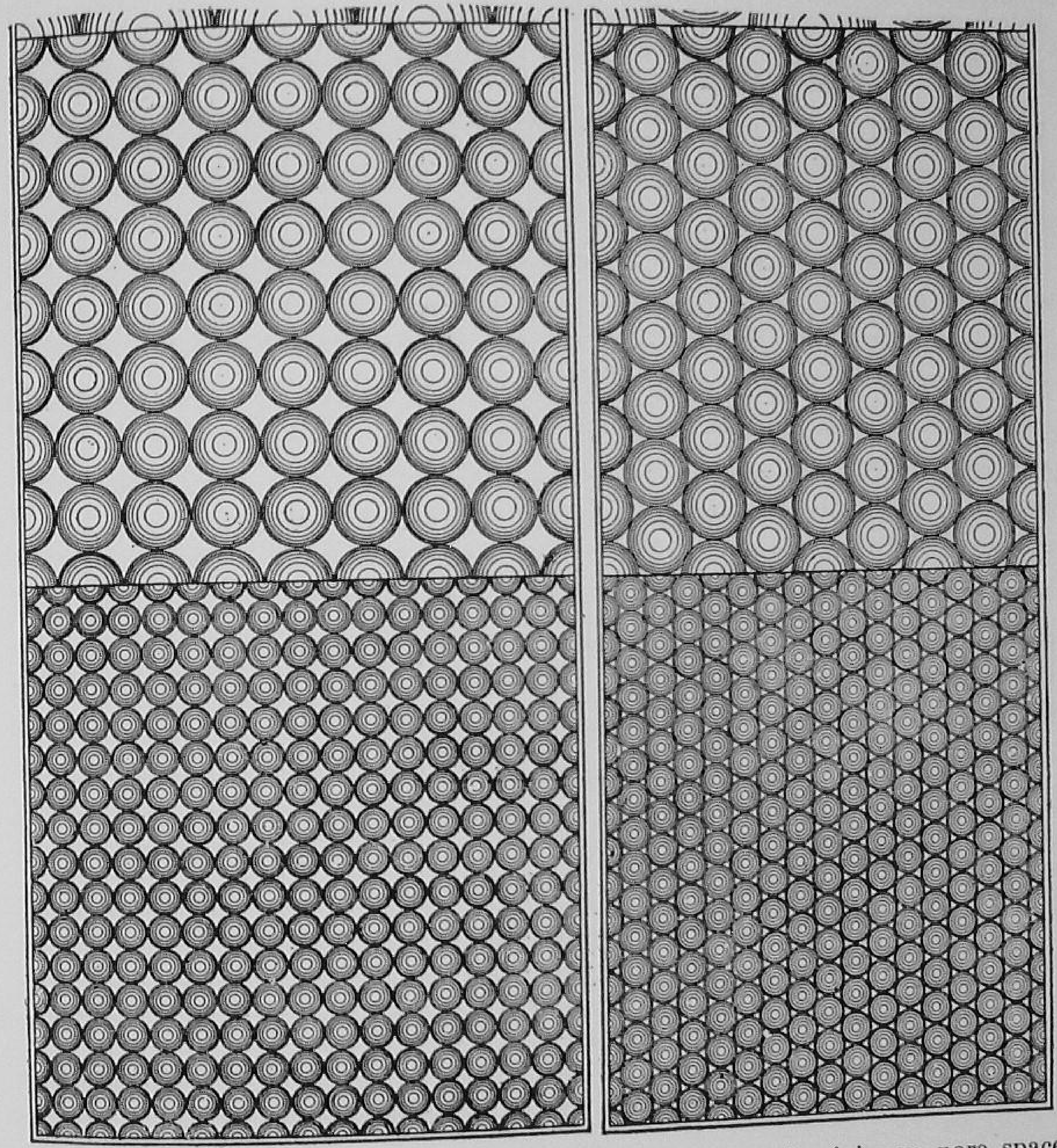


FIG. 101. Illustrating arrangement to give maximum and minimum pore space between spherical soil grains. (*U.S. Geol. Survey 19th Annual Report.*)

percentage pore space, S, it is necessary to know the real and the apparent specific gravity of the soil. The ratio of the apparent to the real specific gravity gives the proportionate space occupied by the soil, and this subtracted from unity gives the pore space. The pore space on a percentage basis is given by the equation:

$$S = 100\left(1 - \frac{A_s}{R_s}\right) \tag{31}$$

where S = the percent pore space.
A_s = the apparent specific gravity.
R_s = the real specific gravity.

The term porosity, equivalent to pore space, is much used in soil mechanics. It is defined as the ratio of the volume of voids (air- and water-filled space) to the total volume of soil plus water and air.

123. Infiltration A property of soils, of great importance to irrigators, is the time rate at which water will percolate into the soil, or the infiltration.

Downward water flow from the soil surface into the surface soil is designated infiltration. Usually, the infiltration rate is much higher at the beginning of a rain or irrigation than it is several hours later. It is influenced by the soil properties and also by the hydraulic slope. Moisture tension, explained in Chapters 9 and 10, may be zero in the surface inch of soil, shortly after wetting, and may be very high a few inches below, thus causing a large downward force (in addition to gravity) pulling the water into the unsaturated soil. Several hours after wetting, these differences in tension may be very small, and gravity then becomes the dominant force causing infiltration. The decrease of infiltration with time after wetting a soil is of importance in rainfall-runoff studies and in irrigation. Water standing on gravelly or coarse sandy soils percolates into the soil so rapidly that the water surface may be lowered several inches in an hour. On fine-textured clay soils, it will collect and stand on soil, seemingly with very little infiltration for many days. Between these two extremes there are many values of infiltration rates. A convenient means of expressing infiltration is in terms of inches lowering of water surface per hour. For example, if an acre of level land at 9 o'clock is covered with water to a depth of 2 in. and at 10 o'clock the water is but 1 in. deep, the infiltration rate is 1 in. per hr, neglecting evaporation losses.

124. Permeability One of the most important properties of soils is the velocity of water flow through the pore spaces caused by a given force. The permeability of soil is defined as the velocity of flow under a hydraulic gradient or slope of unity, in which the driving force is 1 lb per lb of water. Permeability is not influenced by the hydraulic slope, and this is an important point of difference between permeability and infiltration. Also the term permeability is used for designating flow through, or in, saturated soils in any direction. It is most influenced by the physical properties of the soil. Changes in water temperature influence permeability slightly. The meaning of the term *soil*

permeability is explained by the symbols and equations in Chapter 10, where typical measurements of permeability are reported. In saturated field soils, the permeability varies between wide limits; from less than 1 ft per yr in compact clay soils, up to several thousand feet per year in gravel formations. For unsaturated soils, the moisture content is one of the dominant factors influencing the permeability. Table QR shows that permeability is a velocity having the physical dimensions of length divided by time.

125. Water Conductivity Closely related to the permeability of soils is their water conductivity. The difference between the two terms is in language only, not in the soil property. The water conductivity is here defined as *the volume of water that will flow in unit time through a soil column of unit cross-section area owing to the driving force per unit mass corresponding to unit potential gradient.*

Water conductivity thus defined is proportional to the permeability of the soil to water but not equal because water conductivity has the physical dimension of time, and hence its magnitude is independent of changes in force and length units. Study of Chapter 10 will clarify the difference between the terms permeability and conductivity.

126. Depths of Arid-Region Soils As compared to humid-region soils, the soils of arid regions are relatively deep. The importance of having an adequate depth of soil in which to store satisfactory depths of irrigation water at each irrigation is usually given less emphasis than it merits. There are many areas of productive shallow soils in irrigated regions underlain at depths of 1 to 3 ft by coarse gravel, hardpan, or other formations in which plants obtain little or no sustenance. Shallow soils require frequent irrigations to keep crops growing. Excessive deep percolation losses usually occur when shallow soils overlying coarse-textured highly permeable sands and gravels are irrigated. Deep soils of medium texture and loose structure permit plants to root deeply, provide for the storage of large volumes of irrigation water in the soil, and consequently sustain satisfactory plant growth during relatively long periods between irrigations. The volume of water actually absorbed by some plant roots and consumed to produce a crop may be practically the same for shallow and deep soils, yet nearly all practical irrigators recognize that more water is required during the crop-growing season to irrigate a given crop on a shallow soil than is required for the same crop on a deep soil. The larger number of irrigations required for the shallow soils and the greater unavoidable water losses at each irrigation on the shallow soils account for the differences in practical water requirements during the

season. The relation of the depth of soils to their water capacities is considered further in Chapter 9.

127. Plant Food Compounds In order to produce large and satisfactory yields of crops, all soils, both in humid and arid regions, must have adequate supplies of available plant nutrient elements. Many chemical elements are essential to plant growth. Calcium, carbon, hydrogen, iron, magnesium, nitrogen, oxygen, potash, phosphorus, and sulfur are of major importance because they are required in considerable amounts. Because of the sparse or scanty growth of native vegetation on the virgin soils of arid regions the element nitrogen is relatively deficient in arid-region soils. Plants absorb nitrogen in the form of soluble nitrates which are dissolved in the water contained in the capillary form in the soil. In order to assure an adequate supply of available nitrogen it is essential that the irrigated soils contain sufficient amounts of nitrogenous organic matter, which may be supplied from barnyard manure, or from the growing of legume crops as green manures, or from commercial fertilizers. The soil moisture content, the soil structure, and the soil aeration should be made favorable to the bacterial activity which is essential to the formation of nitrates. It has been convincingly demonstrated by many experiments that, when plants are grown in soils having an abundance of available plant food, they consume relatively small amounts of irrigation water per ton or per bushel of crop, but large crops require more water than small ones. It is vitally necessary that arid-region farmers pay particular attention to the maintenance of a high state of productivity in their soils in order to obtain high efficiency in the consumptive use of water in crop production. The low rainfall of arid regions results in a comparatively small amount of leaching, and hence arid soils are usually high in the more important mineral plant-food elements, particularly calcium and potash. The open structure of arid soils permits very favorable aeration to great depths, and consequently favorable bacterial activity occurs at much greater depths in arid- than in humid-climate soils.

128. Excess Soluble Salts The arid-region conditions of low precipitation, high evaporation, and relatively small amounts of soil leaching, though favorable to the occurrence of satisfactory quantities of calcium, phosphorus, and potash in soils, result in the accumulation of excessive quantities of soluble salts that retard or inhibit plant growth. Soils having excess soluble salts are designated as saline soils, and those having excessive exchangeable sodium are designated alkali soils. Even such compounds as sodium nitrates and potassium nitrates,

which normally function as plant nutrients, if accumulated in the soil in excessive amounts, become toxic to plants. There are many areas of highly productive soils in arid regions which are entirely free from salinity and alkali troubles. Moreover, some of these areas probably never will be adversely influenced by the occurrence or the accumulation of excess soluble salts or of exchangeable sodium. In other areas these accumulations are the cause of the widespread sterility and barrenness of arid-region soils. A large amount of research has been directed toward the solution of the salinity and alkali problem in the West. The waters of some arid-region streams and rivers contain appreciable amounts of soluble salts, the actual amounts being influenced by the soil from which the waters flow into the streams and rivers. Because of the importance of salinity and alkali in arid-region soils and their relations to irrigation practices, Chapter 11 is devoted to a consideration of these topics.

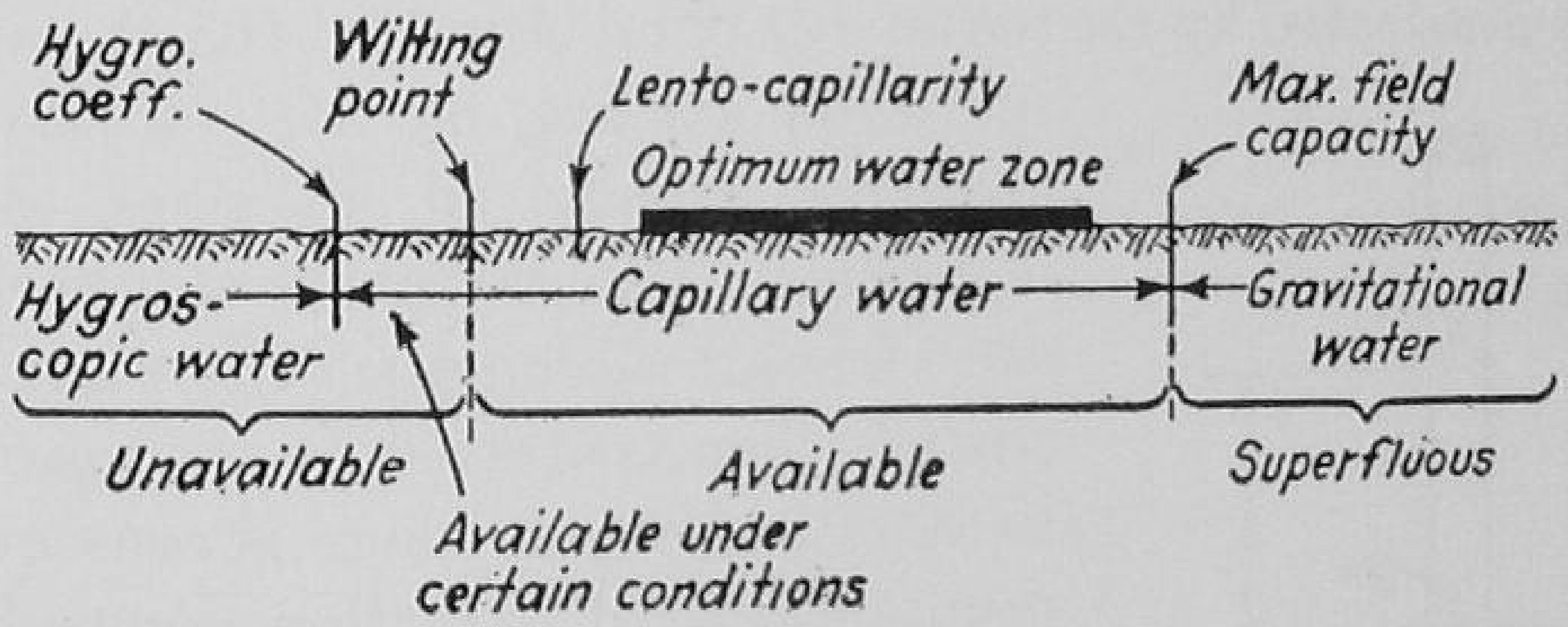


FIG. 102. Classes of soil water and their availability to plants. (From *The Nature and Properties of Soils*, by Lyon and Buckman, The Macmillan Company, New York.)

129. Classes and Availability of Soil Water Soil water may be classified as hygroscopic, capillary, and gravitational. The hygroscopic water is on the surface of the soil grains and is not capable of movement through the action of gravity or capillary forces. Capillary water is that part in excess of the hygroscopic water which exists in the pore space of the soil and which is retained against the force of gravity in a soil that permits unobstructed drainage. Gravitational water is that part in excess of the hygroscopic and capillary water which will move out of the soil if favorable drainage is provided. There is no precise boundary or line of demarcation between these three classes of soil water. The proportion of each class depends on the soil texture, structure, organic matter content, temperature, and the depth of soil column considered. The relation of the classification of soil water to wilting point and maximum field capacity is illustrated in Fig. 102. Water is classified also as unavailable, available, and superfluous or gravitational (Chapter 9). Shown also in Fig. 102 is

the relation of this classification to the first and the relationship of the zone of optimum water to both.

130. Surface Tension Surface tension is due to unbalanced molecular forces. In any body of water the particles in the interior of the liquid

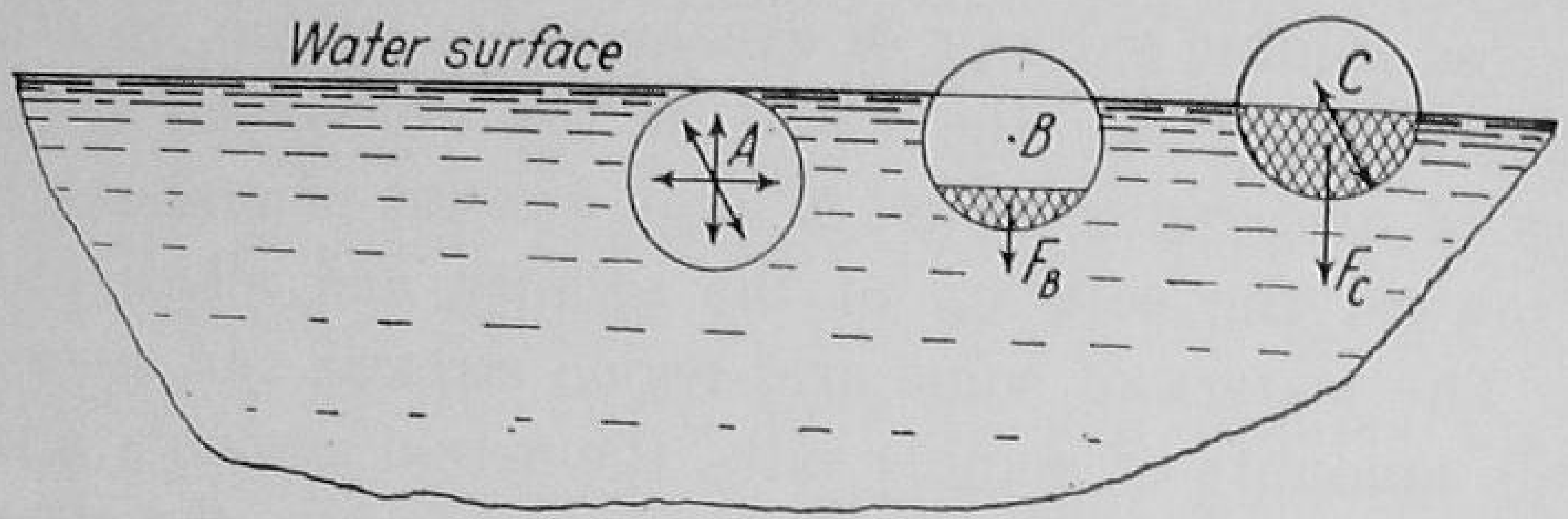


FIG. 103. Illustrating the fact that surface tension is due to unbalanced molecular forces. (From *Mechanics, Molecular Physics and Heat*, by Millikan, Ginn and Company, New York.)

are attracted equally in all directions by the other particles of the liquid, as illustrated by the particle at point A in Fig. 103. A particle on the water surface, on the contrary, is not attracted equally on all sides, since the molecules of the air surrounding the particle exert less attraction upon the water-surface particle than is exerted by the interior particles of the liquid. There is consequently a resultant inward attraction along a line perpendicular to the surface of the liquid as illustrated in points B and C of Fig. 103.

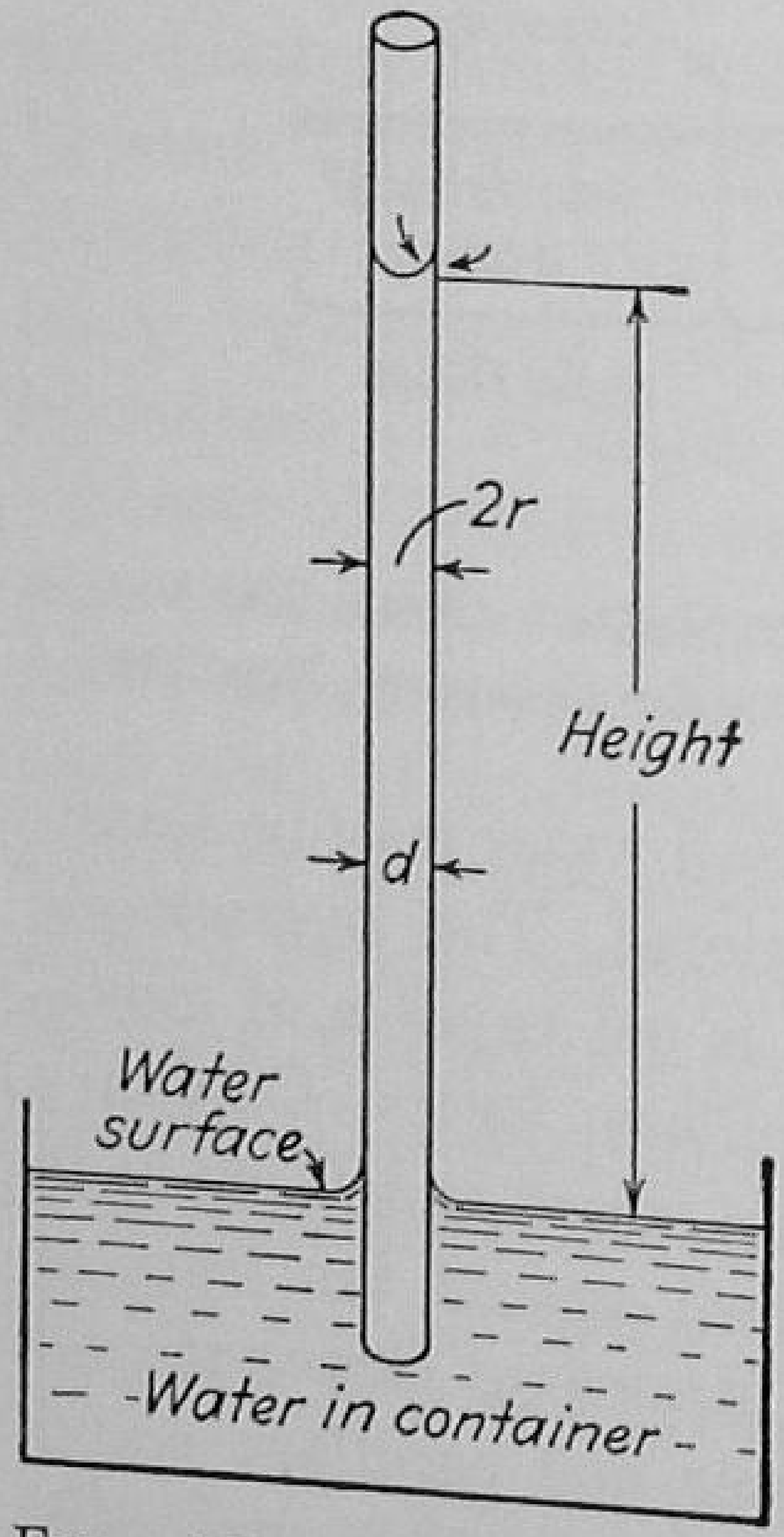


FIG. 104. Showing that water rises in a capillary tube, owing to surface tension, to a height well above the surface of the water in the container.

131. Tension Heads The water in the capillary tube illustrated in Fig. 104 is held in the position shown at a height h_t above the water surface by an upward force due to surface tension in the water.

Let F_u = the total upward force.
F_d = the total downward force.

Then $F_u = F_d$ because the water is at rest. For the purpose of this analysis, the angle of contact between the water and the glass tube (a in Fig. 104) is considered zero. Then the upward force is equal to the circumference of the tube times the surface tension of the water, and the downward force is equal to the volume of water times its specific weight w.

Using symbols and equations

$$F_d = \pi r^2 h_t w = F_u = 2\pi r T$$

It follows that

$$h_t = \frac{2T}{rw} \tag{32}$$

The h_t of equation 32 is the height to which water will rise in a capillary tube of radius r as the result of the surface tension of the water T. It is here designated the tension head. Unsaturated soil pores, like the capillary tube of Fig. 104, develop concave water surfaces and suction forces or tensions that tend to pull water in soils from points of high moisture percentages to points of lower moisture percentages.

Multiplying each side of equation 32 by w there results

$$wh_t = \frac{2T}{r} \tag{32a}$$

Each side of equation 32a is a force intensity (F/L^2) due to tension. Using metric units for T and w of equation 32, since the surface tension of water is 75.6 dynes per cm and its specific weight is 980 dynes per cc, it follows that

$$h_t = \frac{2 \times 75.6}{980r} = \frac{0.15}{r} \tag{33a}$$

Equation 33a gives the height in centimeters to which water at 4° C will rise in a capillary tube of radius r centimeters (Table QR).

Applying essentially the same reasoning as underlies equation 33a to ideal soils in which the capillary tubes are triangular in cross section, Keen has shown that the maximum height of rise of water in centimeters is given approximately by the equation:

$$h_t = 0.75/r \quad \text{and} \quad h = 1.5/d \tag{33b}$$

in which r is the radius and d the diameter of the soil particles in millimeters.

Because of the great variability in natural soils and the changes in size of capillary tubes, the actual heights of rise of water by capillary action are usually less than the theoretical heights computed from equation 33b. In general terms, under average conditions capillarity acts freely to 4 or 5 ft, fairly to 10 ft, and slowly to 30 or more ft.

Equation 33b shows that the film tension of soil moisture increases as the radius of the capillary water film decreases. Soils of a given texture and structure having low percentages of water have, there-

fore, high moisture tensions, whereas the same soils having high percentages of water have low moisture tensions. These facts explain observed soil and water relations, such, for example, as the decrease in capillary water with increase in distance above a water table when at equilibrium.

132. Tensiometers The tension or suction force of unsaturated soils for water is measured by means of porous cups filled with water,

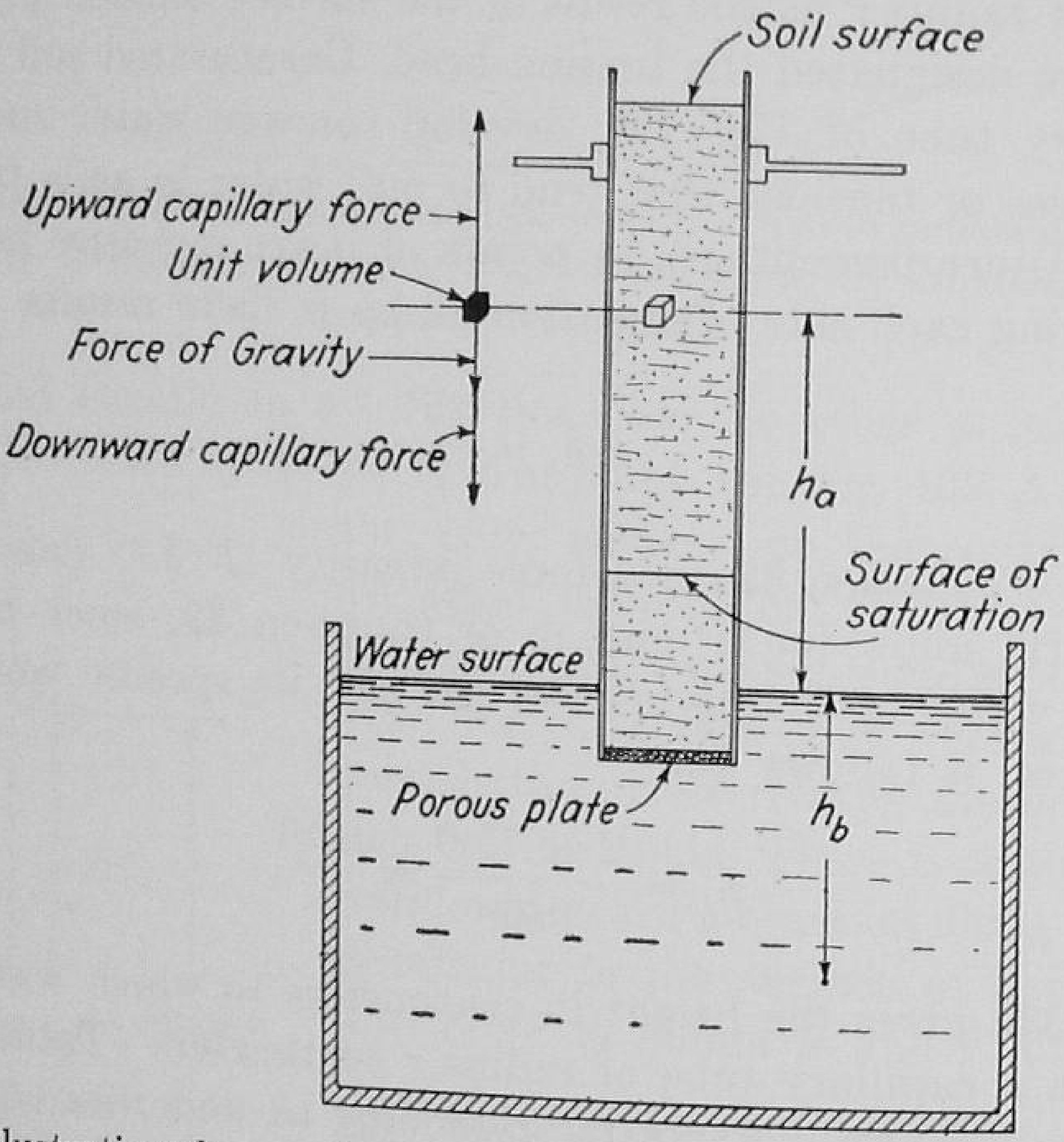


FIG. 105. Illustrating the equal magnitude of the vertical forces which act on the water in any unit volume of a soil in which the capillary water is at equilibrium with the ground water.

placed in the soil, and attached to a mercury manometer. When the cups are placed in a dry soil, water moves from the porous cup into the soil because of the soil moisture tension and causes the mercury to rise in the manometer. The use of tensiometers is explained in Chapter 10 under the study of soil moisture energy relations and the flow of water in unsaturated soils.

133. Equilibrium Water Conditions Consider a unit volume within a vertical soil column at a height h_a above the surface of free water as illustrated in Fig. 105. By equilibrium conditions it is meant that there are no unbalanced forces and consequently no flow of moisture. The attainment of equilibrium conditions is difficult. It may require much

time together with the maintenance of constant temperature and prevention of evaporation. However, for the purpose of this chapter it is necessary only to assume the attainment of equilibrium conditions. Assume two further conditions:

(*a*) That the unit volume selected is 1 cc; and

(*b*) That the mean moisture content of the soil within the cubic centimeter is 20 percent by volume.

Then the actual weight of water within the cubic centimeter is 0.2 gm. For convenience, the 0.2 gm of water is illustrated by the black cube to the reader's left of the soil column. The force of gravity is pulling down on the 0.2 gm of water, and the magnitude of the gravitational force is $0.2 \times 981 = 196.2$ dynes. The cubic centimeter of soil is completely surrounded by soil containing capillary water, and hence there must be a downward capillary tension. But, since under equilibrium conditions there are no unbalanced forces and no flow, it follows that the upward tension on the 0.2 gm of water is equal in magnitude to the sum of the downward tension and the gravity force. The tension forces are relatively large in soils of low moisture content and small in soils of high moisture content. Hence in the upper part of the cubic centimeter the moisture content must be less than it is near the lower part; otherwise the upward tension force could not exceed the downward tension. Therefore, at equilibrium moisture conditions, the moisture content must decrease as the height of the soil above the free water surface increases.

The conclusion from the above discussion is well supported by technical analysis of basic energy relations of soil moisture and also by the results of experiments on the distribution of moisture in soils. From measurements of water distribution in many soil columns of small cross section, McLaughlin found, subject to certain minor discrepancies near the free water surface, that the moisture content of different soils after many days of contact with free water decreased with increase in height above the free water surface. Figure 106 represents the moisture distribution after a vertical column of Idaho lava ash soil had been in contact with water for 46 days. The free water surface was 66 in. below the surface of the soil column. From a point about 15 in. above the water surface the moisture content decreased with increase in height from more than 30 percent to less than 15 percent.

Veihmeyer, Israelsen, and Conrad studied the distribution of moisture within a thin layer of soil after it had been subjected to a centrifugal force of approximately 1000 times gravity in a moisture

equivalent centrifuge. The results of their work are given in Fig. 107. The inner soil surface (the surface nearest the axis of the moisture equivalent machine) is represented by the top of the figure, and the

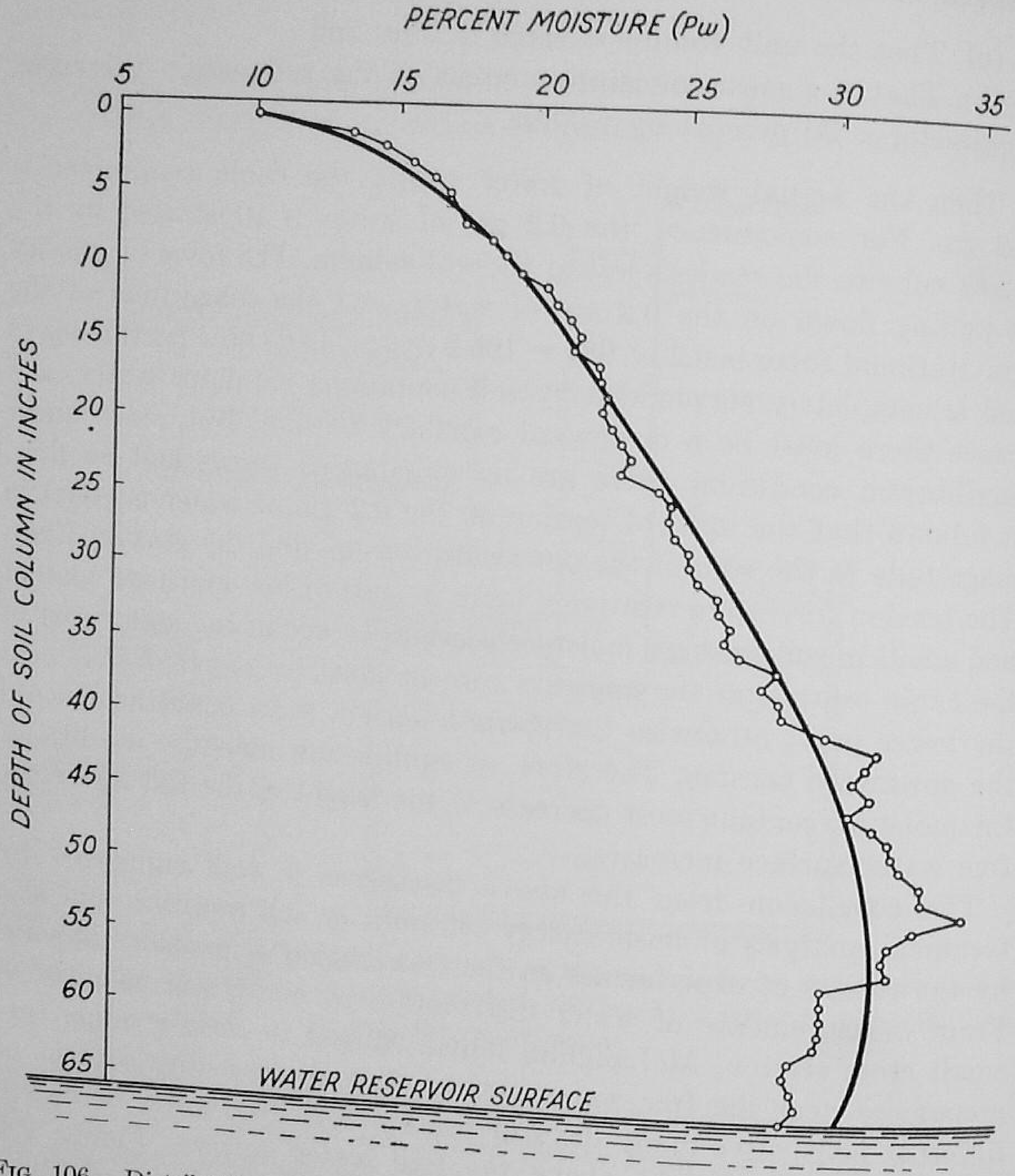


FIG. 106. Distribution of capillary water in a vertical column of Idaho lava ash soil after 46 days in contact with a water reservoir. (*U.S.D.A. Bul.* 1221.)

outer soil surface by the bottom. The rotation of the block of soil in the machine throws the gravitational water out through a perforated wall at the outer surface of the soil column. Hence the curve of Fig. 107 shows the distribution of the moisture which took place to form an equilibrium condition with the throw-off force induced by the rotation of the machine. There is a marked increase in moisture

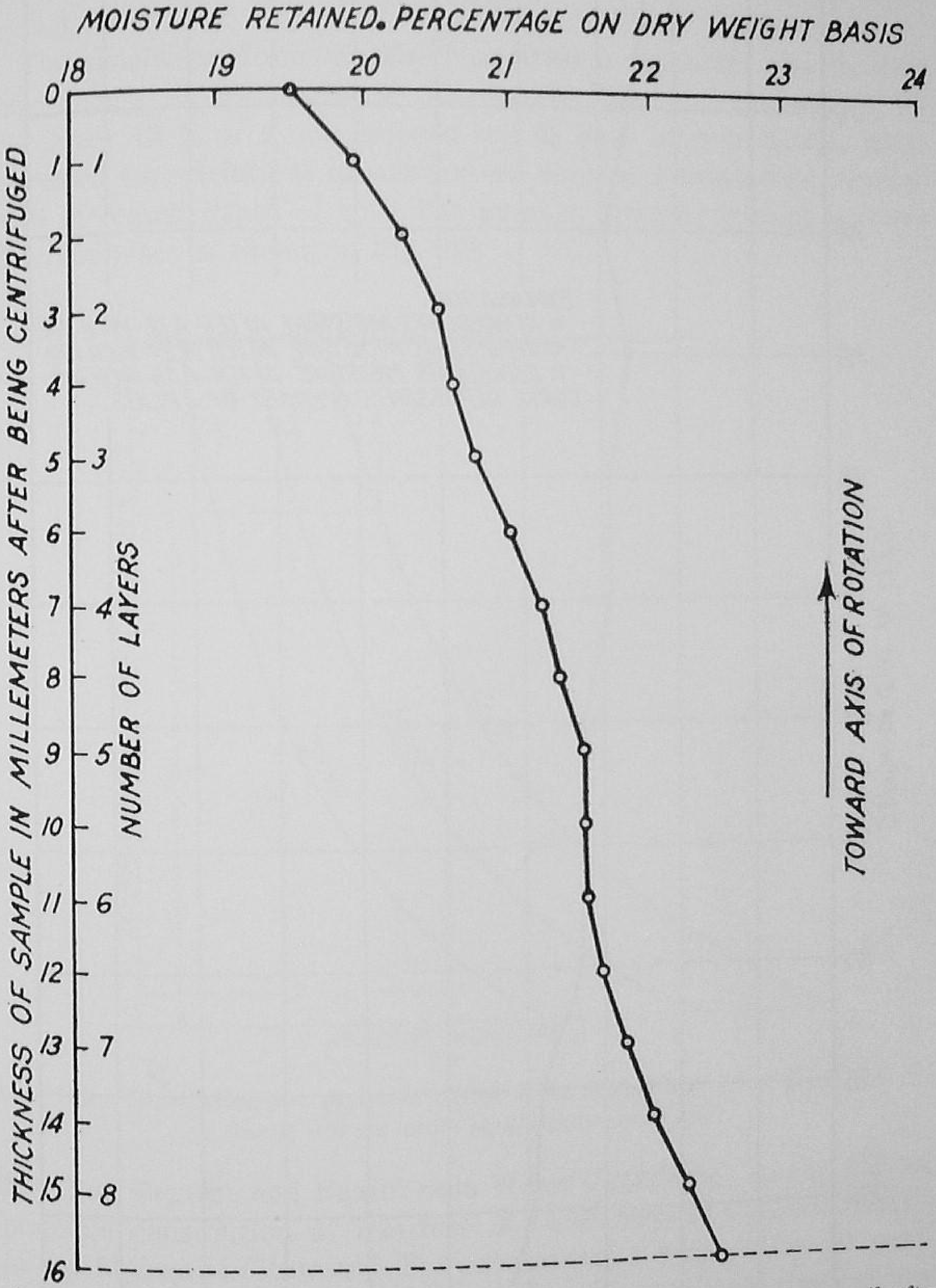


FIG. 107. Moisture distribution in a 60-gram sample of yolo clay loam soil after being subjected to a centrifugal force of 1000 times gravity for a period of ½ hr. (*Calif. Agr. Exp. Sta. Tech. Paper* 16.)

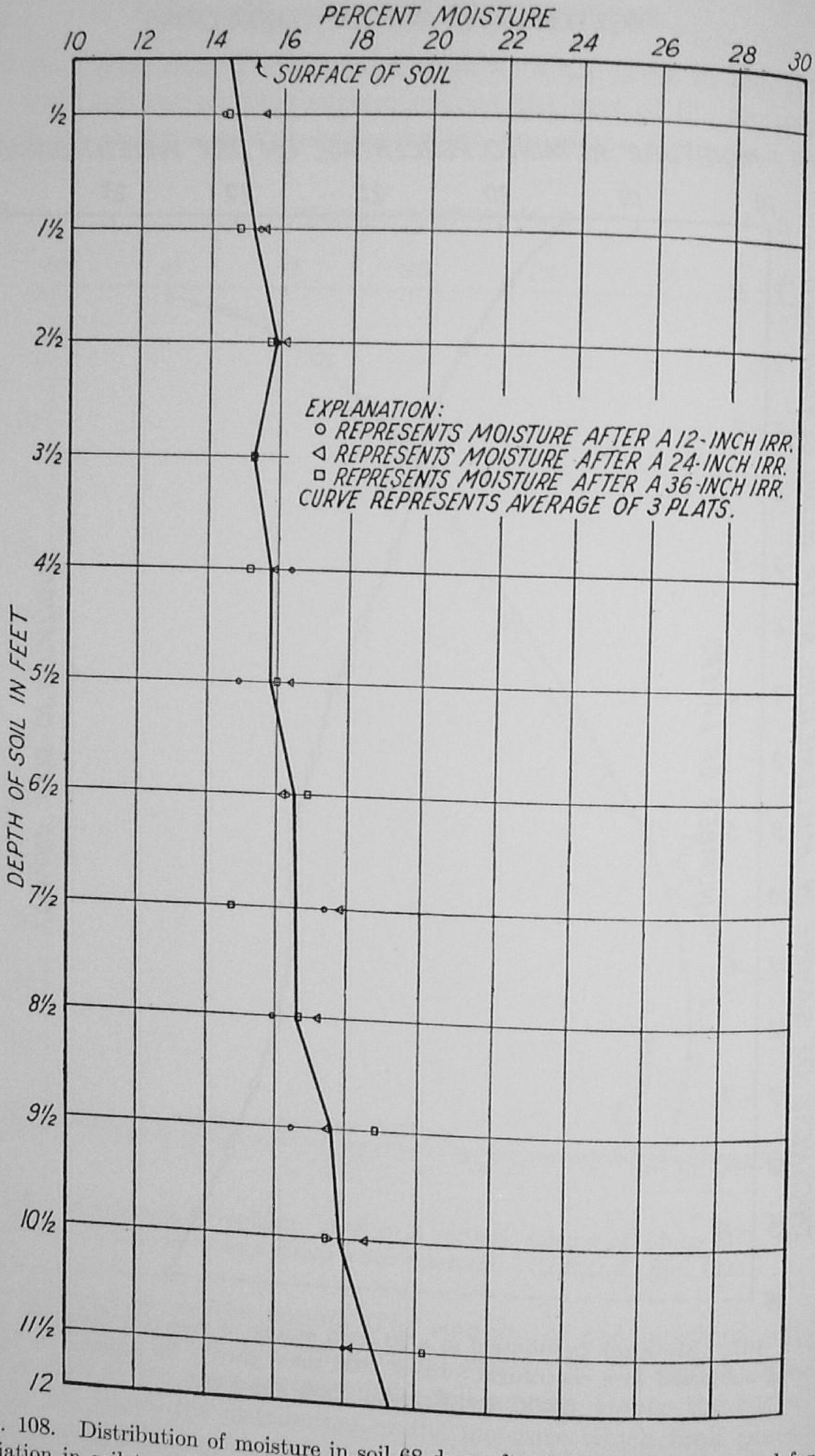


Fig. 108. Distribution of moisture in soil 68 days after irrigation as corrected for variation in soil texture, thus showing distribution that would have occurred in a soil of uniform texture. (*Calif. Agr. Exp. Sta. Hilgardia*, Vol. 2, No. 14.)

content from the inner to the outer surface, analogous to the increase in field-soil moisture content at equilibrium with increase in depth of soil.

The conclusion from the above analysis is supported also by field experiments on soil-moisture distribution. The moisture content of the upper 12 ft of a non-cropped soil 68 days after irrigation, when corrected for variations in soil texture, showed a substantial increase with increased depth of soil. The average moisture content in three different plats is shown in Fig. 108.

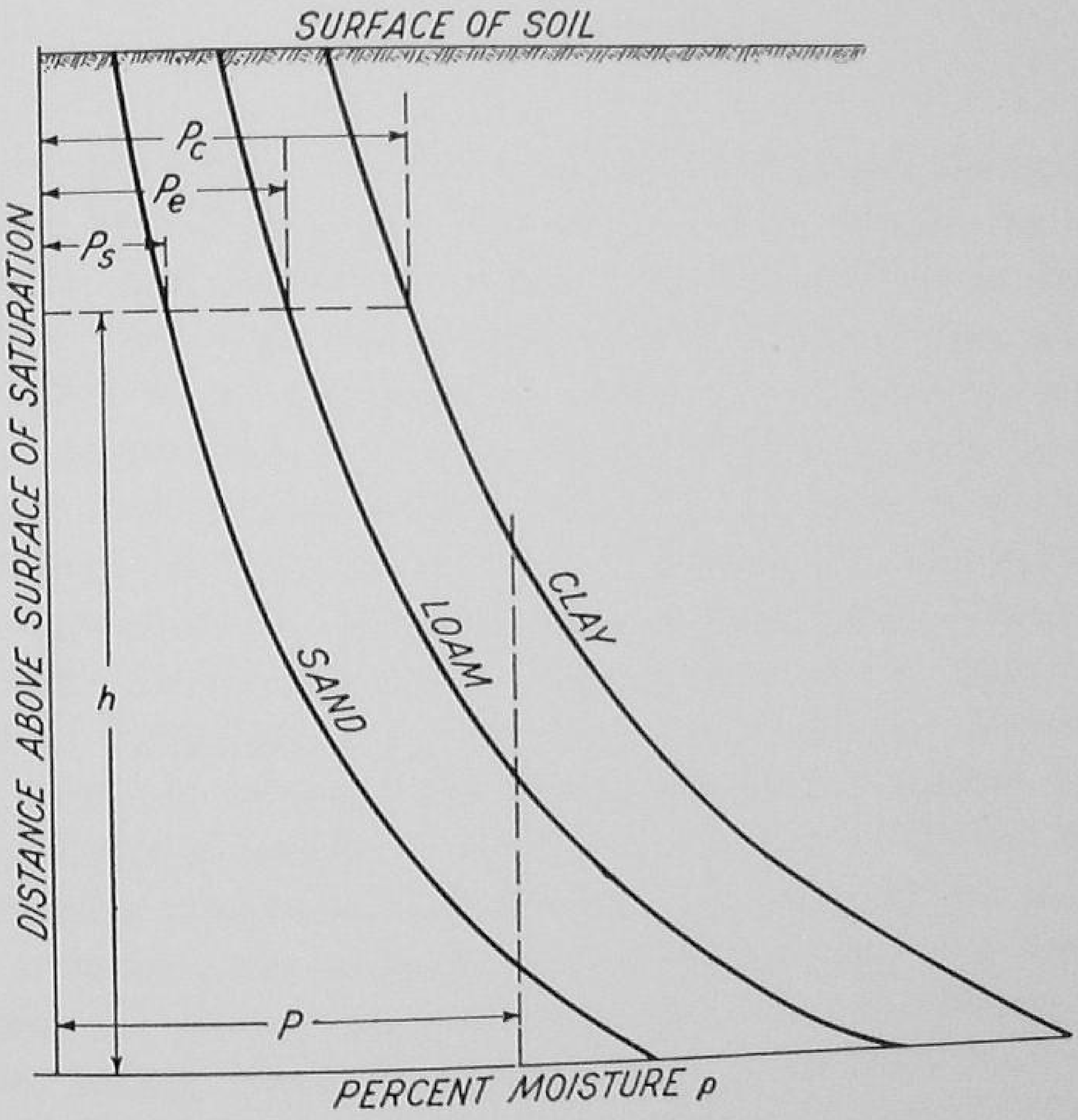


FIG. 109. Illustrating the probable distribution of capillary water in soils of different texture under equilibrium conditions.

134. Soil Texture and Equilibrium Water Conditions In Fig. 109 the probable distribution of moisture in three soils of different texture at equilibrium is illustrated. For convenience, a point in the saturated surface is selected as origin, the horizontal coordinate representing percentage capillary water, and the vertical coordinate representing distance vertically above the saturated surface. Three things are indicated by Fig. 109.

1. That under equilibrium conditions the moisture content of a soil decreases as the distance from the surface of saturation increases.

2. That, at a given distance above the saturated surface as represented by h, the clay soil has a higher percentage of moisture than the loam, and the loam has a higher percentage than the sand.
3. That any given moisture percentage, at equilibrium, will be at the highest point in the clay, and the next highest in the loam, and lowest in the sand.

The soil-moisture distribution under equilibrium conditions illustrated in Fig. 109 is in harmony with basic facts of film and moisture tensions and equality of upward and downward forces.

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7-SEP 1956
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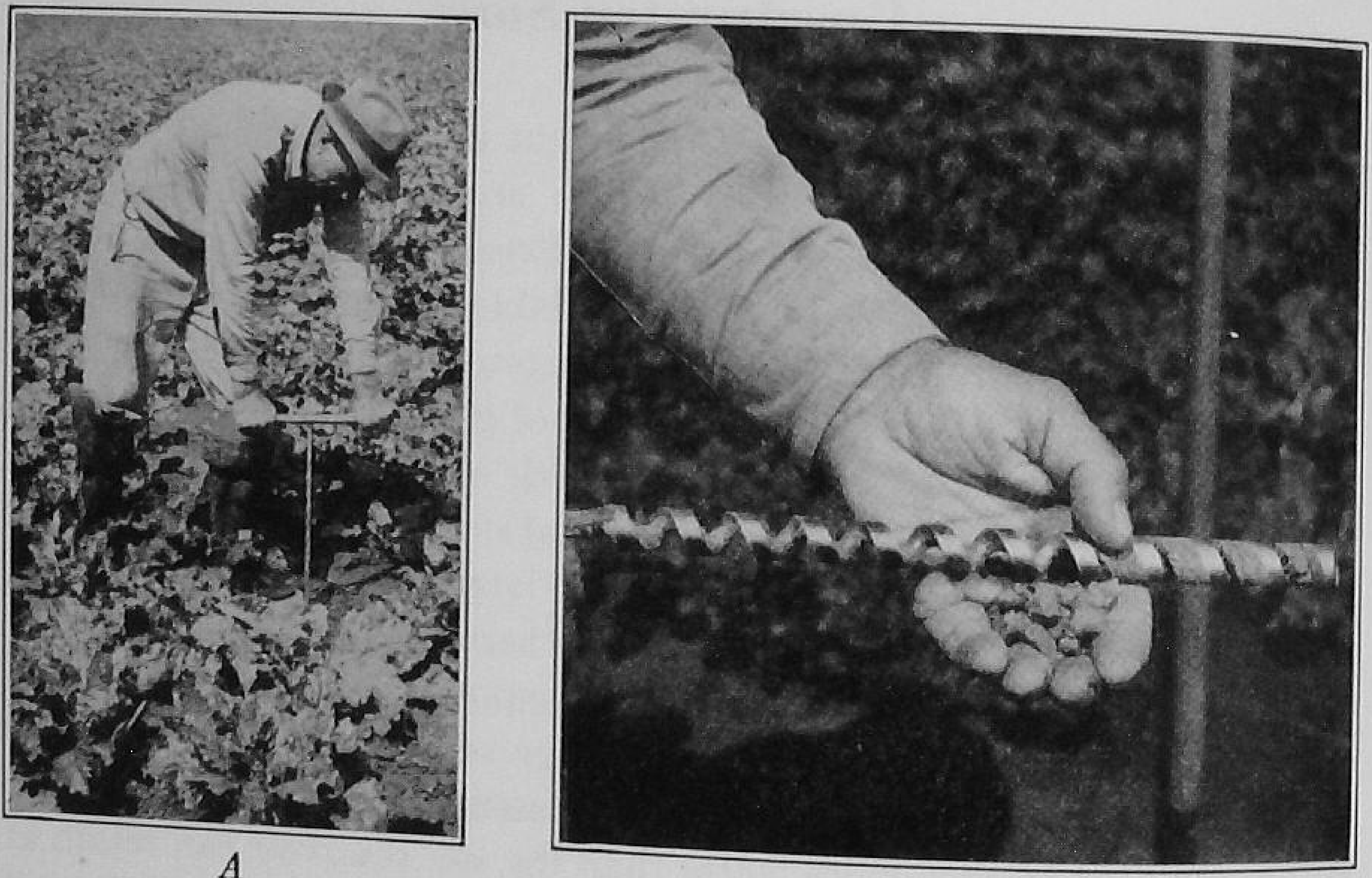
9
Storage of Water in Unsaturated Soils

The storage of water in soils is important in humid and arid regions. That some humid-climate soils produce crops despite the elapse of many days, and sometimes weeks, between periods of rainfall, is evidence of their capacity to store available water, since all growing plants require water continuously. In irrigated regions the capacity of soils to store available water for the use of growing crops is of special importance and interest because the depth of water to apply in each irrigation and the interval between irrigations are both influenced by their storage capacity. Irrigated soils of large water-storage capacity may produce profitable crops in places where, and at times when, the shortage of irrigation water makes it impossible to irrigate as frequently as would be desirable. Knowledge of the capacity of soils to retain available irrigation water is also essential to efficient irrigation. If the irrigator applies more water than the soil reservoir can retain at a single irrigation the excess is wasted. If he applies less than the soil will retain the plants may wilt from lack of water before the next irrigation, unless water is applied more frequently than otherwise would be necessary. In this chapter, attention is given to the storage of irrigation water in soils. Water losses which result from deep percolation below the root zone of crops cannot be seen. They can be measured approximately by subtracting from the depths of water applied in single irrigations, less the runoff, the storage capacity depths of the various soils for water.

135. Forms of Water Stored In irrigated regions, water is stored in the soil in both capillary and gravitational form. The storage of moisture in unsaturated soils that is available to plants is of major importance and is therefore given special attention here. However, in localities where the late-season water supply is always low, and surface storage

reservoirs are impracticable or economically prohibitive, storage of water in saturated soils in the gravitational form is sometimes advantageous. Excessive application of water for the purpose of water storage may cause the ground water to rise and become injurious to crops during the early part of the season.

It is important to find the available water capacity for different soils, i.e., the field capacity less the moisture content at permanent wilting. Some soils having high field capacities also have high wilting points, thus making the available water capacity rather low, requiring frequent irrigation. The depth of available water that can be stored in-



A B

FIG. 110. A soil auger helps to show when water is needed and the depth of water penetration from irrigation. (Courtesy Union Pacific Railroad Company.)

creases with the root-zone depth. Methods of estimating the depths and volumes of the water that may be stored and made available to crops are considered in this chapter, after a brief description of a soil auger and soil-sampling tube.

136. The Soil Auger It is highly desirable that irrigation farmers observe by inspection and sometimes by measurement the quantities of moisture in their soils. Boring or drilling deeply into the soils of arid regions for the desired information concerning soil moisture conditions is essential.

Two types of soil augers are used: one a spiral-shaped bit made from a 1½-in. carpenter's standard wood auger bit, and one 2-in. post-hole auger made especially for boring into the soil.

The spiral-bit auger, well below the soil surface in Fig. 110*A*, is illustrated in Fig. 110*B*. The screw-point and the side-cutting edges of a carpenter's auger are removed in preparing the bit for soil boring. The spiral auger is light in weight and convenient to carry around. When using it in compact soils care is necessary to avoid boring too deeply at one time and thus causing the auger to lodge in the soil. The post-hole auger, illustrated in Fig. 111, does not involve this danger because when filled with soil it does not easily advance further.

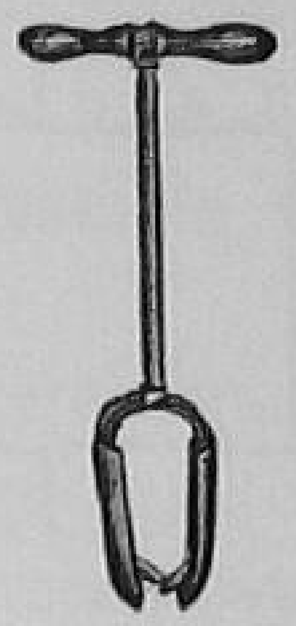


FIG. 111. Post-hole auger. Small-diameter augers of this type are used for studying the distribution of irrigation water in soil. (Courtesy Iwan Brothers.)

Physical properties of soils cannot be satisfactorily determined from inspection of the land surface. It is especially helpful to irrigation farmers to study the texture, structure, and depth of their soils by means of a soil auger or a soil-sampling tube in order to adjust their irrigation methods and practices according to the needs of the soils. Losses of water through deep percolation from shallow soils may be reduced by efficient application of water if the irrigator is well informed concerning the texture and depth of his soil.

137. An Improved Soil-Sampling Tube F. H. King, one of America's pioneer soil scientists, designed and used a steel tube for sampling soils. The "King soil tube" has been improved by Veihmeyer and associates of the California Agricultural Experiment Station. After several years' experience with different soil-sampling devices in irrigation and soil-moisture studies, Veihmeyer concluded that the samples of soil obtained with the improved soil-sampling tube give more accurate and consistent results than those obtained with other sampling devices. In soils containing gravel it is frequently difficult, and sometimes impossible, to obtain samples by means of a soil auger, whereas with a properly made sampling tube it is possible to cut through layers of gravel and obtain satisfactory samples.

As illustrated in Fig. 112, each tube consists of three parts: a tube of seamless steel of the desired length, a driving head, and a point. Each end of the tube is threaded to facilitate attachment of the head and the point. A special hammer drives the tube into the soil.

In the design of the improved tube, precautions have been taken, as reported by Veihmeyer, to reduce the difficulties of removing the tube from the soil. Where samples need be taken to great depths, 12 to 18 ft, a puller made of two automobile jacks mounted on a base and connected at the top by a yoke may be needed to draw the tube from the soil.

Taylor and Blaney, working in southern California, have designed and built an efficient soil tube jack with which they have drawn tubes after sampling the soil to a depth of 18 ft. They have pulled tubes whenever it was possible to drive them with a 30-lb hammer.

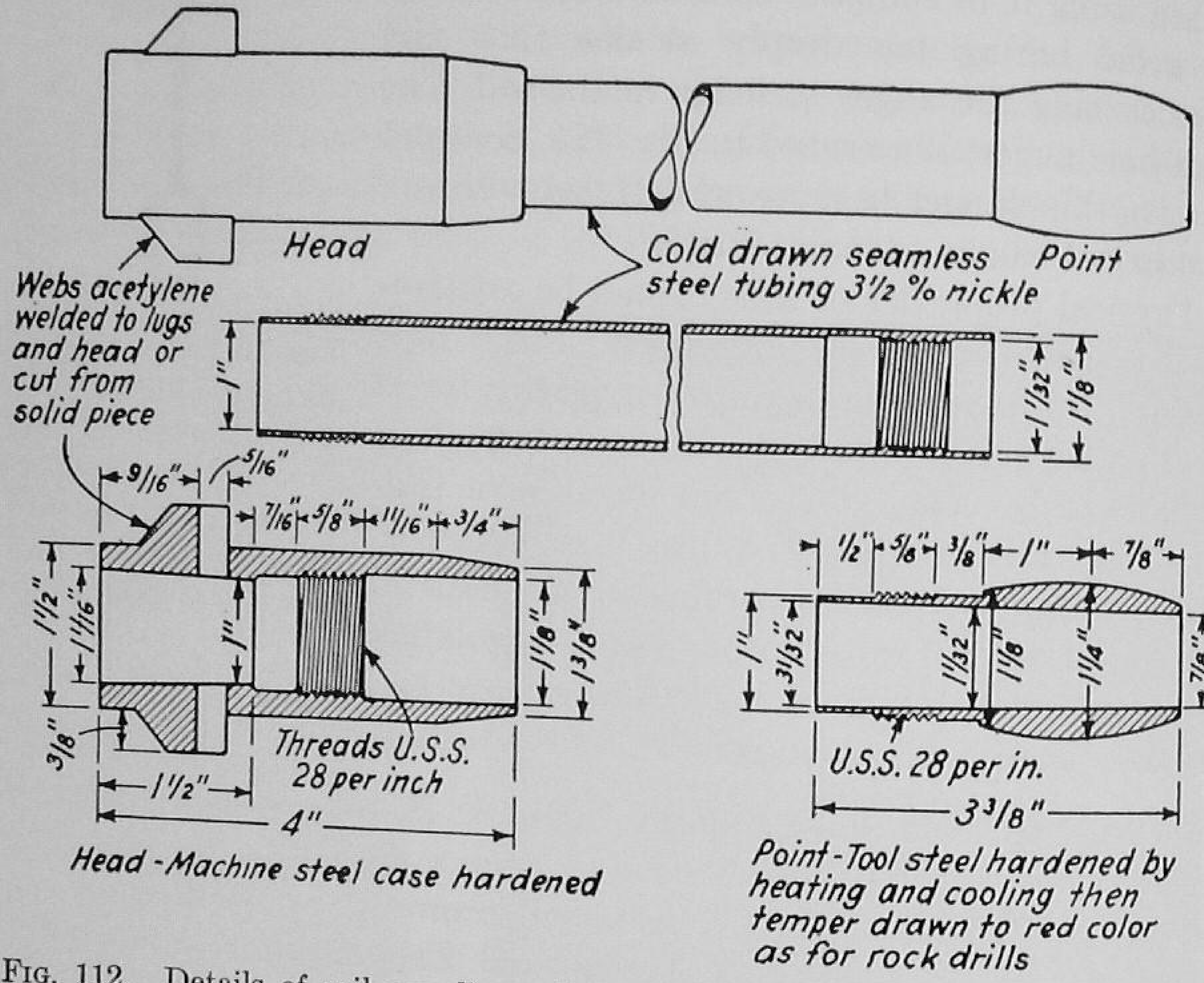


FIG. 112. Details of soil-sampling tube. (Williams and Wilkins Company, *Soil Sci.*, Vol. 27, No. 2.)

138. Measuring the Soil-Moisture Content Direct methods of measuring the moisture content of soils, though tedious and costly, have substantial value. The practice is to bore or drive to the desired depths with a soil auger or a soil tube, place samples of the moist soil in cans provided with covers, and take the soil samples to a laboratory for weighing and drying. Samples of 100 or more grams of moist soils are kept in an oven having a temperature of 105° to 110° C until the soil is free from moisture. The loss of weight in drying, divided by the weight of the water-free soil, and multiplied by 100 is the moisture percentage on the dry-weight basis, represented by the symbol P_w. For example:

Weight of moist soil	100 gm
Weight of water-free soil	80 gm
Loss of weight in drying	20 gm

Then P_w (i.e., the moisture percentage on the dry-weight basis) =

20/80 × 100 = 25. Measurements of soil-moisture content are sometimes reported on the *wet-weight basis;* that is, in the above example, the moisture percentage on the wet-weight basis = 20/100 × 100 = 20. The apparent advantage of the wet-weight basis is the simplicity of computation if 100 gm of moist soil are used. In reality, however, the wet-weight basis is irrational because the reference base for the percentage computation, i.e., the weight of the wet sample of soil, varies according to the moisture content of the soil.

Interpretations of the significance and influence of different quantities of water in the soil, both in relation to water storage and to plant growth, are facilitated by converting the moisture percentage on the dry-weight basis to the volume basis. The percentage on a volume basis is defined as the volume of water per unit volume of space within the body of soil. For example, if a cubic foot of space within the soil contains ¼ cu ft of air, ¼ cu ft of water, and ½ cu ft of solid soil particles, the percentage of moisture on the volume basis, represented by the symbol P_v, is 25. Drying the soil in an oven, as a means of extracting the water from it, results in a loss of water in the form of vapor. It is therefore desirable to convert dry-weight basis moisture percentages P_w to volume percentages P_v. The apparent specific gravity of the soil, represented by the symbol A_s as stated in Chapter 8, is defined as the ratio of the weight of a given volume of soil, say 1 cu ft, to the weight of an equal volume of water, and:

$$P_v = A_s P_w \tag{34}$$

Based on equation 34, Table 21 gives the moisture percents on the volume basis that are equivalent to different percents on the dry-weight basis.

139. Field-Moisture Capacity The percentage of water P_{fc} that a well-drained soil retains at a specified time after flooding is designated the field-moisture capacity. It is influenced largely by the texture, structure, and organic content of the soil. In soils having ground water near the soil surface the field capacity is influenced by the position of the water tables. The time after irrigation at which the soil moisture content is equal to the field capacity is taken as 2 to 5 days, but this time period cannot be accurately fixed because so many variable factors influence soil-moisture flow. Probably the moisture in irrigated soil during the growing season is always moving. However, the velocities at which soil moisture flows vary widely according to the moisture content of the soil. Although the dynamic properties of soil moisture make a precise determination of field-

TABLE 21

Moisture Percents on the Volume Basis, P_v, Equivalent to Various Percents on the Dry-Weight Basis, P_w, for Soils of Different Apparent Specific Gravity, A_s, Based on Equation 34, $P_v = A_s P_w$

Moisture Percent on Dry-Weight Basis (P_w)	Apparent Specific Gravity (A_s)							
	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
1.0	1.10	1.20	1.30	1.40	1.50	1.60	1.70	1.80
1.2	1.32	1.44	1.56	1.68	1.80	1.92	2.04	2.16
1.4	1.54	1.68	1.82	1.96	2.10	2.24	2.38	2.52
1.6	1.76	1.92	2.08	2.24	2.40	2.56	2.72	2.88
1.8	1.98	2.16	2.34	2.52	2.70	2.88	3.06	3.24
2.0	2.20	2.40	2.60	2.80	3.00	3.20	3.40	3.60
2.2	2.42	2.64	2.86	3.08	3.30	3.52	3.74	3.96
2.4	2.64	2.88	3.12	3.36	3.60	3.84	4.08	4.32
2.6	2.86	3.12	3.38	3.64	3.90	4.16	4.42	4.68
2.8	3.08	3.36	3.64	3.92	4.20	4.48	4.76	5.04
3.0	3.30	3.60	3.90	4.20	4.50	4.80	5.10	5.40
3.2	3.52	3.84	4.16	4.48	4.80	5.12	5.44	5.76
3.4	3.74	4.08	4.42	4.76	5.10	5.44	5.78	6.12
3.6	3.96	4.32	4.68	5.04	5.40	5.76	6.12	6.48
3.8	4.18	4.56	4.94	5.32	5.70	6.08	6.46	6.84
4.0	4.40	4.80	5.20	5.60	6.00	6.40	6.80	7.20
4.2	4.62	5.04	5.46	5.88	6.30	6.72	7.14	7.56
4.4	4.84	5.28	5.72	6.16	6.60	7.04	7.48	7.92
4.6	5.06	5.52	5.98	6.44	6.90	7.36	7.82	8.28
4.8	5.28	5.76	6.24	6.72	7.20	7.68	8.16	8.64
5.0	5.50	6.00	6.50	7.00	7.50	8.00	8.50	9.00
5.2	5.72	6.24	6.76	7.28	7.80	8.32	8.84	9.36
5.4	5.94	6.48	7.02	7.56	8.10	8.64	9.18	9.72
5.6	6.16	6.72	7.28	7.84	8.40	8.96	9.52	10.08
5.8	6.38	6.96	7.54	8.12	8.70	9.28	9.86	10.44
6.0	6.60	7.20	7.80	8.40	9.00	9.60	10.20	10.80
6.2	6.82	7.44	8.06	8.68	9.30	9.92	10.54	11.16
6.4	7.04	7.68	8.32	8.96	9.60	10.24	10.88	11.52
6.6	7.26	7.92	8.58	9.24	9.90	10.56	11.22	11.88
6.8	7.48	8.16	8.84	9.52	10.20	10.88	11.56	12.24
7.0	7.70	8.40	9.10	9.80	10.50	11.20	11.90	12.60
7.2	7.92	8.64	9.36	10.08	10.80	11.52	12.24	12.96
7.4	8.14	8.88	9.62	10.36	11.10	11.84	12.58	13.32
7.6	8.36	9.12	9.88	10.64	11.40	12.16	12.92	13.68
7.8	8.58	9.36	10.14	10.92	11.70	12.48	13.26	14.04
8.0	8.80	9.60	10.40	11.20	12.00	12.80	13.60	14.40
8.2	9.02	9.84	10.66	11.48	12.30	13.12	13.94	14.76
8.4	9.24	10.08	10.92	11.76	12.60	13.44	14.28	15.12
8.6	9.46	10.32	11.18	12.04	12.90	13.76	14.62	15.48
8.8	9.68	10.56	11.44	12.32	13.20	14.08	14.96	15.84
9.0	9.90	10.80	11.70	12.60	13.50	14.40	15.30	16.20
9.2	10.12	11.04	11.96	12.88	13.80	14.72	15.64	16.56
9.4	10.34	11.28	12.22	13.16	14.10	15.04	15.98	16.92
9.6	10.56	11.52	12.48	13.44	14.40	15.36	16.32	17.28
9.8	10.78	11.76	12.74	13.72	14.70	15.68	16.66	17.64

moisture capacity very difficult, it is feasible to approximate field capacity by soil-moisture determinations of undisturbed field soils. Methods and procedure in making these determinations are given in Article 141 together with some typical results.

140. Basis of Available Capacity Soil-Moisture Storage Provided the available moisture capacity of a soil is known, the depth of water that may be stored in the root-zone soil can be determined as follows:

Let P_{ac} = the available field capacity; that is, the field capacity minus the field moisture percentage at permanent wilting.

W = the dry weight of the soil to be moistened, pounds.

w = the weight of water necessary to increase soil-moisture content from permanent wilting percentage to field capacity, pounds.

Then

$$w = \frac{P_{ac}W}{100}$$

The depth of water applied in a single irrigation is usually expressed in acre-inches or acre-feet per acre, or simply surface inches or surface feet. Thus, if 6 acre-inches were spread uniformly over 1 acre the depth of irrigation would be 6 in., or 0.5 ft. In practice, however, if ½ acre-foot of water is used to irrigate an acre the result is considered a ½-ft irrigation, regardless of lack of uniformity in distribution of the water over the surface.

Let A = area of land irrigated in square feet.

A_s = the apparent specific gravity of the soil.

d = the depth of water to be applied, feet.

D = depth of soil to be moistened, feet.

Then, the weight of soil to be moistened is

$$W = 62.4\ A_sAD \text{ lb}$$

and the weight of water necessary to add is

$$w = 62.4dA \text{ lb}$$

Substituting for W and w these values in the above equation, there results

$$62.4dA = 62.4 \frac{P_{ac}}{100} A_sAD$$

from which

$$d = \frac{P_{ac}}{100} A_sD \qquad (35)$$

In the application of equation 35, d may be computed in inches if D is also in inches. For example, assume that the available field capacity of soil having an average apparent specific gravity of 1.4 is 5 percent and it is desired to add an average of 5 percent moisture to the upper 4 ft. Then

$$d = \frac{5}{100} \times 1.4 \times 4 = 0.28 \text{ ft} = 3.36 \text{ in.}$$

Similar problems may be solved for different available capacities and root-zone depths, with sufficient accuracy for practical purposes, by the use of Table 22.

141. Determinations of Field Capacity To make direct measurements of the field capacity P_{fc} of soils for water, it is essential to give careful attention to the following conditions:

(*a*) Assure complete capillary saturation by adding an excessive depth of irrigation water.

(*b*) Reduce to a minimum the surface-evaporation losses immediately after irrigation.

(*c*) Eliminate transpiration losses by working on non-cropped plots.

(*d*) Observe the time rates of decrease in moisture content by making moisture determinations at different times after irrigation.

(*e*) Select for the study of field capacity a plot under which the water table is at great depth.

Excessive percolation of water vertically downward from a plot completely flooded will assure wetting the surface soil to field capacity. Average soils have a pore space of about 50 percent. If it is desired to assure complete capillary saturation of the upper 6 ft of a loam soil, the necessary depth of water to apply may be computed somewhat as follows: The total voids if the soil were completely dry at the beginning would be $50/100 \times 6 = 3$ ft. Moisture determinations before flooding show an average of 2 in. of water per foot depth of soil. The remaining pore space is 4 in. per foot of soil, or 24 in. for the 6 ft. An irrigation of 24 in. would then completely fill the pore space if percolation were prevented at the 6-ft depth. This depth would seem ample to assure saturation.

The surface-evaporation losses immediately after flooding may be reduced to a minimum by spreading a deep straw mulch. Experiments conducted on a deep loam soil at Logan, Utah, showed that a 12-in. depth of straw mulch reduced the surface evaporation to a negligible amount.

The selection of a particular time after flooding as representing the field-moisture capacity is difficult. The rate of downward flow of water after flooding soils on which there is no plant growth decreases from day to day, and yet it may continue for weeks and months. In reality the

TABLE 22

Depth of Irrigation Water in Inches Required to Add Different Available Field-Moisture Capacities to 1 Ft of Soil for Soils Having Different Apparent Specific Gravities. Based on Equation 35,

$$d = \frac{P_{ac}A_sD}{100}$$

Available Field Moisture Capacities (P_{ac})	Apparent Specific Gravity (A_s)							
	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
4.0	0.58	0.62	0.67	0.72	0.77	0.82	0.86	0.91
4.2	.60	.65	.71	.76	.81	.86	.91	.96
4.4	.63	.68	.74	.79	.84	.90	.95	1.01
4.6	.66	.72	.77	.82	.88	.94	.99	1.05
4.8	.69	.75	.81	.86	.92	.98	1.04	1.09
5.0	.72	.78	.84	.90	.96	1.02	1.08	1.14
5.2	.75	.81	.87	.94	1.00	1.06	1.12	1.19
5.4	.78	.84	.91	.97	1.04	1.10	1.16	1.23
5.6	.81	.87	.94	1.01	1.08	1.14	1.21	1.28
5.8	.83	.90	.97	1.04	1.11	1.18	1.25	1.32
6.0	.86	.93	1.01	1.08	1.15	1.22	1.30	1.37
6.2	.89	.97	1.04	1.12	1.19	1.26	1.34	1.41
6.4	.92	1.00	1.08	1.15	1.23	1.31	1.38	1.46
6.6	.95	1.03	1.11	1.19	1.27	1.35	1.43	1.50
6.8	.98	1.06	1.14	1.22	1.31	1.39	1.47	1.55
7.0	1.01	1.09	1.18	1.26	1.34	1.43	1.51	1.60
7.2	1.04	1.12	1.21	1.30	1.38	1.47	1.56	1.64
7.4	1.07	1.15	1.24	1.33	1.42	1.51	1.60	1.69
7.6	1.09	1.19	1.28	1.37	1.46	1.55	1.64	1.73
7.8	1.12	1.22	1.31	1.40	1.50	1.59	1.68	1.78
8.0	1.15	1.25	1.34	1.44	1.54	1.63	1.73	1.82

capacity at equilibrium is the moisture held after the downward movement of moisture has ceased. The very slow attainment of equilibrium conditions necessitates, in practice, an arbitrary selection of the time when down drainage becomes negligible and the moisture content of field soils at this time is designated the field capacity. In coarse-textured sand soils downward flow of water will become negligible more quickly than in the fine-textured clay soils. The time that the observer may select after flooding may vary from one to many days. If the time

selected is too short and the downward flow is significant, the observed field capacity will be greater than the true capacity, provided evaporation and transpiration losses have been prevented. On the other hand, if the after-irrigation moisture content of crop-producing soils that have been heavily irrigated is considered as representing approximately the field capacity, it is probable that the rapid evaporation and transpiration losses in a few days following irrigation may reduce the moisture content to an amount less than the true capacity.

The distribution of water 68 days after irrigation as presented in Fig. 108 (Chapter 8) substantiates the statement that, at equilibrium, the moisture capacity of the upper few feet of soil is relatively high when the water table is high and low when the water table is low.

Using experimental plots near Glendale, Arizona, in Salt River Valley, Hilgeman measured the field capacity of the upper 8 ft of a silty clay loam on May 1, 1944, seven days after irrigation. The plots were irrigated on February 21, 1944, and April 24, 1944, after which no further irrigation was applied until March 11, 1946. The soil-moisture percentages on May 1, 1944, ranged from 21.3 on the surface foot to 35.0 in the sixth foot and averaged 27.8 in the 8 ft. Twenty-two months later the average moisture percentage was only 19.9, although the plots were kept bare and had received light winter rains. Nearly 10 in. of water were lost from the 8 ft of soil, of which more than two-thirds was lost from the upper 4 ft.

The term "field capacity" has been used by Colman to refer to that point at which the rate of change of moisture content has become so low as to be insignificant in comparison with early rates. Using this concept of field capacity, Hilgeman found that field capacity was attained 10, 14, and 19 days after wetting in the 0- to 12-, 12- to 18-, and 18- to 30-in. zones, respectively. Field capacity in the 30- to 54-in. zone was apparently attained prior to 5 days after wetting. The 54- to 66-in. zone, which was wetted entirely by drainage after the irrigation water was shut off, increased to a constant moisture content by the fourteenth day.

Hilgeman concluded that the determination of the field capacity for the soil studied is difficult and subject to considerable error. There was no single time after wetting that was satisfactory for all depths. Considerable differences were obtained in two experiments. These differences were apparently due to differences in the moisture content of the subsoil.

142. Water-Storage Measurements Some water-storage measurements have been made by direct methods in connection with the study

of irrigation of important crops. Others have been made on non-cropped soil with a view to finding the maximum quantity of water that may be stored in a field soil by increasing the moisture content, from the minimum ordinarily found in the field, to the field capacity. The method of procedure in making field-moisture-capacity determinations as outlined in Article 141 may also be followed to find the depth of water that may be stored in any field soil. After having found the percentages of moisture in the soil before, and also following, irrigation, the equivalent depths of water may be computed by means of equation 35 if the apparent specific gravity is known. The depth of water found in the form of soil moisture at any time from one to three days after irrigation, minus the depth before irrigation, gives approximately the depth that may be stored as available soil water.

In California, Utah, Oregon, and Washington, attention has been given to a study of the storage of water in soils. The results of some of these studies are here briefly reported.

143. California Studies In an investigation of the economical use of water for alfalfa in Sacramento Valley, California, conducted by Adams and others, studies were made on capacities of soils for irrigation water. Soil-moisture determinations were made immediately before irrigation and from one to four days after. The studies do not represent precise measurements of maximum field capacity, but rather they show the average amounts of water stored by irrigation in soils of different texture at various time periods after irrigation.

In order to interpret these and similar determinations of soil moisture in terms of depths of water applied and retained, it is necessary to determine the apparent specific gravity of the soil A_s. The average values of A_s* for each class of soil are given in Table 23, which contains a summary of the average depths of water applied to each soil and also the depths retained in the upper 6 ft a few days after irrigation. Because of the fact that alfalfa was growing on each of the farms, estimates were made of probable evaporation and transpiration losses between the time of irrigation and moisture tests following. These estimated losses added to the amounts actually retained are also reported in Table 23, page 200.

The number of inches of water in each foot of soil both before and after irrigation are shown in Figs. 113 to 116. In the coarser-textured soils, i.e., the fine sandy loams and silt loams, borings were made to a depth of 9 ft, whereas in the clay loams and clays, moisture tests were

* For the best results of storage capacity A_s should be measured in various depths of the root zone, because in many soils it changes with depth.

made only in the upper 6 ft of soil. Each figure contains the moisture equivalent as determined by the Briggs-McLane method, and the pore space as computed from determinations of apparent and real specific gravity.

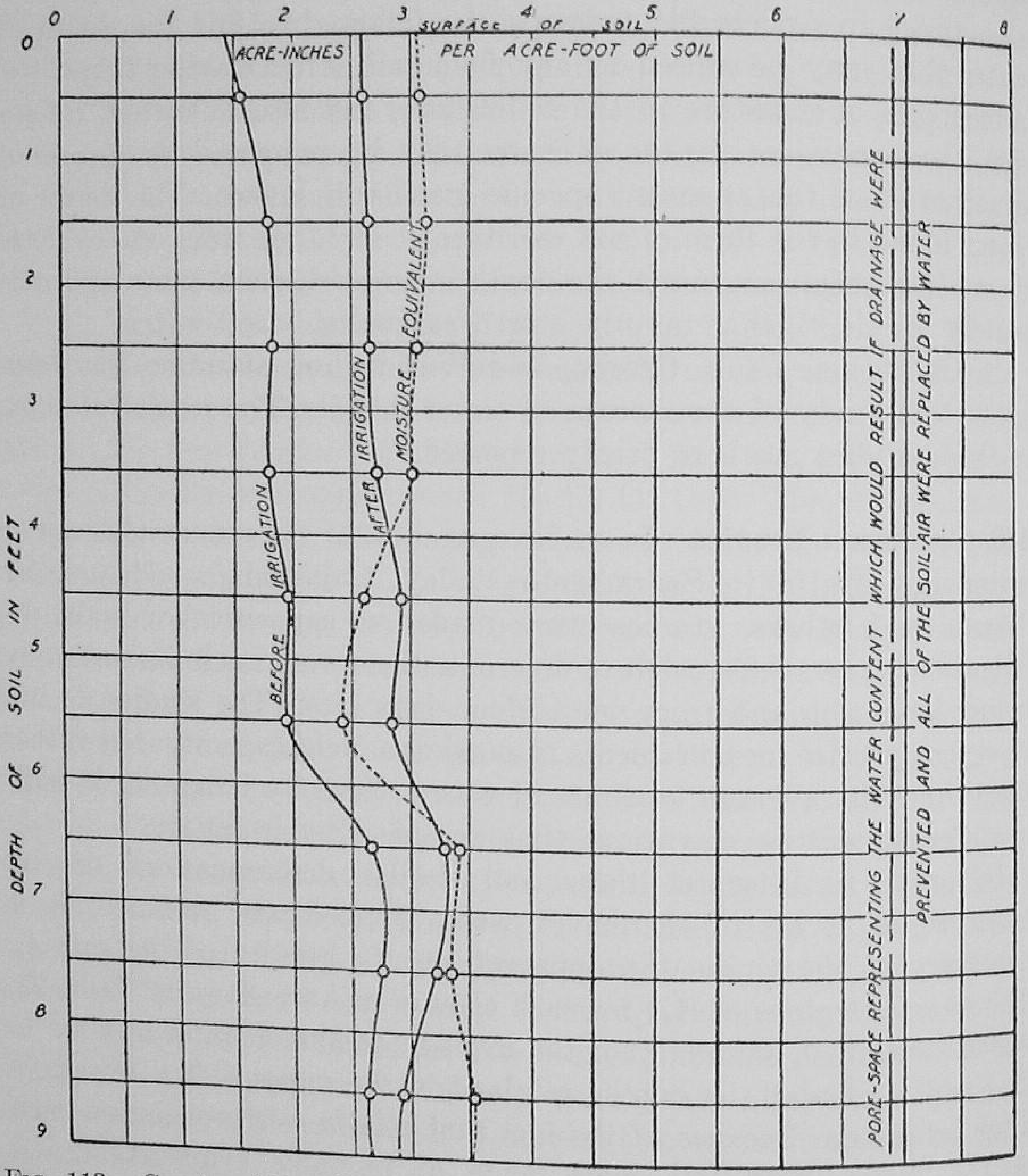


FIG. 113. Graphs of the water content before and after irrigation, moisture equivalent, and pore space of silt-loam soils having fine sandy-loam subsoils. Each water-content curve is the average of 62 borings. (*U.S.D.A. J. Agr. Research*, Vol. 13, No. 1.)

Figures 113 and 114 show that the water penetrated below the 9-ft depth in the silt-loam soils. Figure 115 shows penetration below the 6-ft depth in the clay-loam soils, and Fig. 116 indicates a small moisture increase in the 12-ft depth of the yolo loam soils. The volume of air space in excess of the moisture content after irrigation

is greatest in the coarse-textured soils and smallest in the fine-textured ones. In the upper 6 ft the silt loams having fine sandy loam subsoils held an average of 2.73 in. of water per foot of soil; the silt loams, 3.20 in.; the clay loams, 3.49 in.

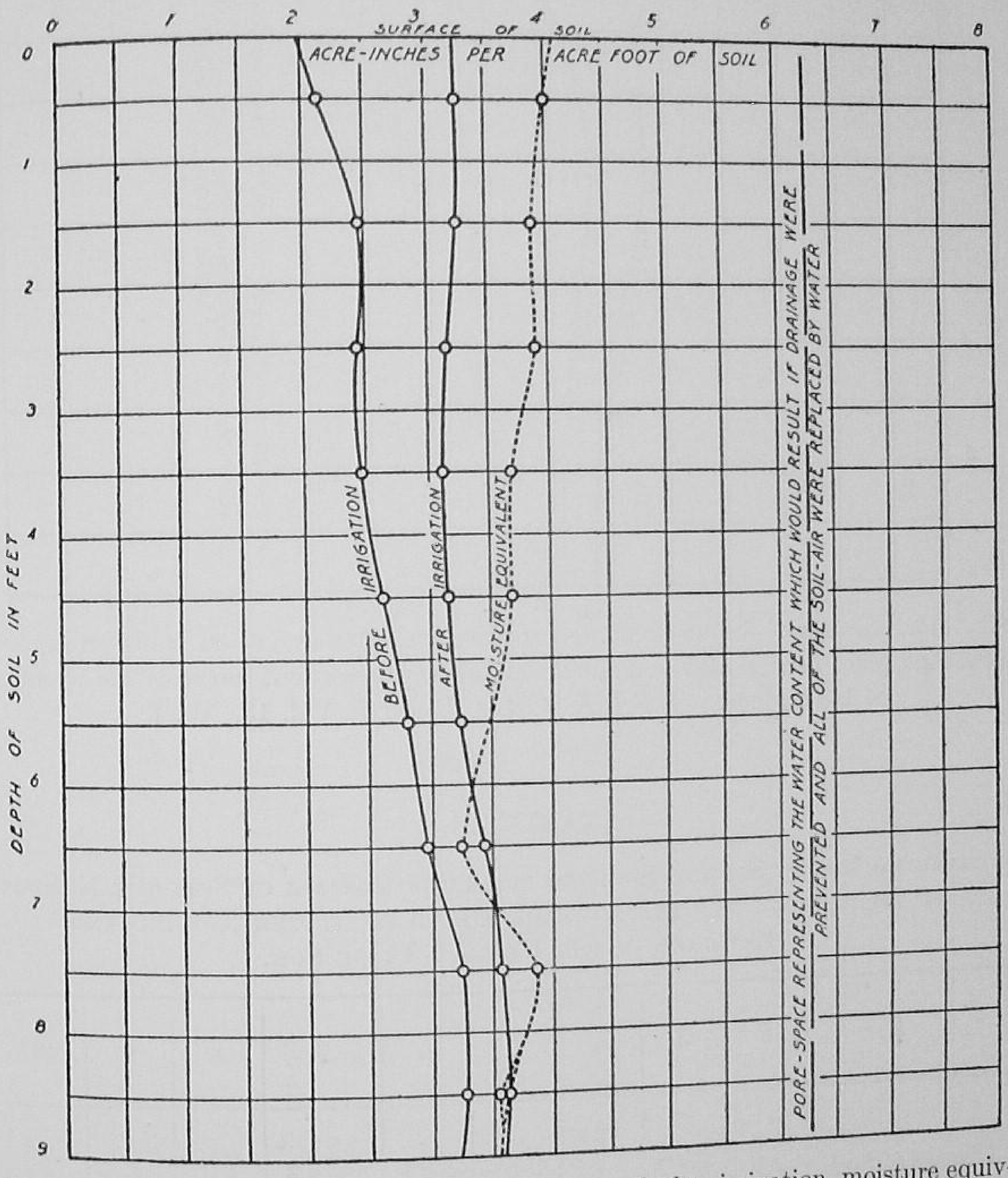


FIG. 114. Graphs of the water content before and after irrigation, moisture equivalent, and pore space of silt-loam soils. Each water-content curve is the average of 87 borings. (*U.S.D.A. J. Agr. Research*, Vol. 13, No. 1.)

The average moisture contents of each foot of soil for six experimental plots at the University Farm at Davis, California, before and after irrigation are given in Fig. 116. Each plot was irrigated differently, but the smallest depth of water applied was 6 in. in each irrigation. It appears that some water penetrated below the 12-ft depth. However, the data from 10 to 12 ft inclusive are based on

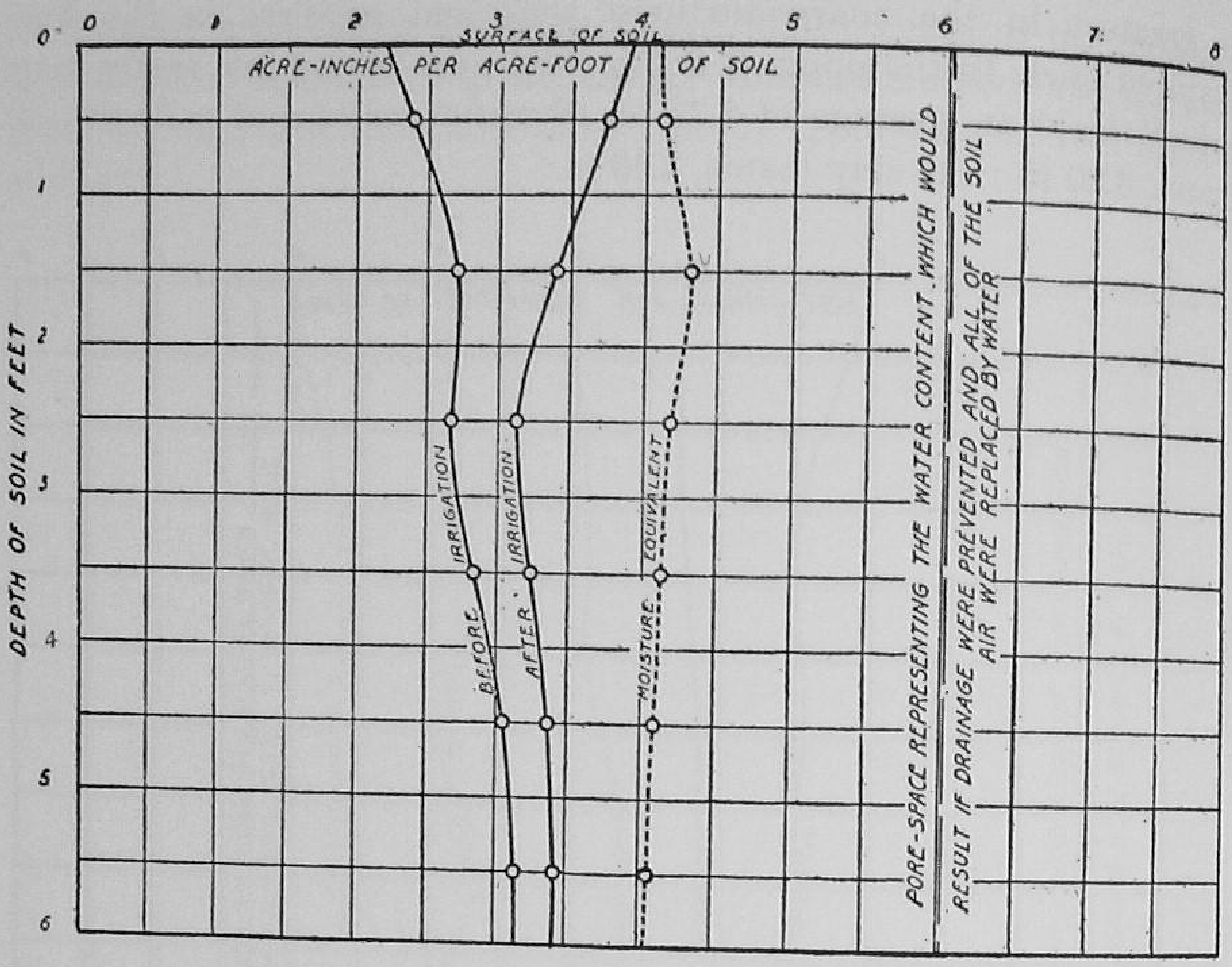


Fig. 115. Graphs of the water content before and after irrigation, moisture equivalent, and pore space of clay-loam soils. Each water-content curve is the average of 148 borings. (*U.S.D.A. J. Agr. Research*, Vol. 13, No. 1.)

TABLE 23

Sacramento Valley Studies Showing for Four Classes of Soil the Number of Irrigations; and the Average Depth of Water Applied and Retained in the Upper 6 Ft of Soil

1	2	3	4	5	6	7	8	9	10
Classes of Soil	Number of Borings	Apparent Sp. Gr. (A_s)	Average Number of Irrigations	Depth Applied, Inches	Depth Retained, Inches	Depth Retained Plus Evaporation, Inches	Per Cent Retained	Per Cent Retained Plus Evaporation	Farms in the Group
Silt loams with sandy loam subsoils	62	1.15	3.0	15.02	5.52	6.60	36.8	43.9	2
Silt loams	87	1.31	3.3	12.81	4.24	5.32	33.1	41.5	3
Clay loams	148	1.35	4.0	8.78	3.50	4.56	39.8	52.0	5
Clays	43	1.69	4.0	4.72	2.20	3.28	46.8	69.4	2

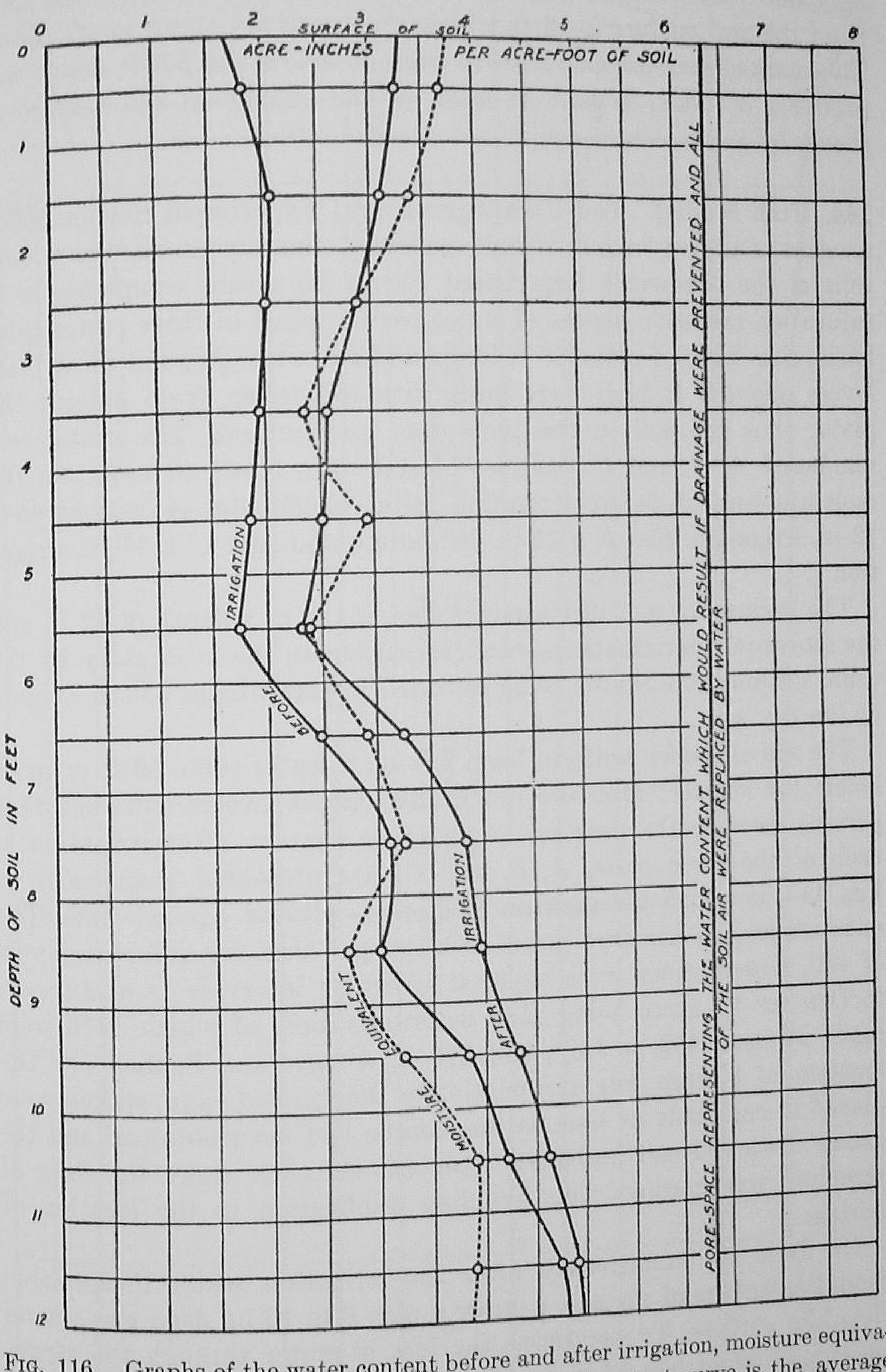


FIG. 116. Graphs of the water content before and after irrigation, moisture equivalent, and pore space of yolo loam soils. Each water-content curve is the average of 6 plots for three consecutive years, and the average of 147 borings. (*U.S.D.A. J. Agr. Research*, Vol. 13, No. 1.)

only one year's studies and are therefore less precise than the data from the soil surface to 6 ft which are based on three years' work. The marked increase in moisture content below the 5.5-ft depth was probably a result, in part at least, of the change in soil texture as shown by the moisture-equivalent determination.

144. Utah Studies The Utah Agricultural Experiment Station made a series of measurements of field-moisture capacity on the deep loam soils of the Greenville Experiment Farm. To insure completeness of saturation excessive depths of water were applied to three rectangular basin, non-cropped plats, 38 ft long and 33 ft wide. Around these plats levees about 2 ft high were built with soil taken from outside the plats; thus the soil in the plats was undisturbed. The plats were numbered *A*, *B*, and *C*. Samples of soil were taken to ascertain the moisture content before irrigation, after which plat *A* was given a 12-in. irrigation, plat *B* a 24-in. irrigation, and plat *C* a 36-in. irrigation.

The borings for moisture samples were made to a depth of 12 ft, and the moisture determinations were carried out in the laboratory by the usual methods, the results being recorded in percentages of the weights of the dry soil.

The soil is a deep uniform loam having a water table 50 ft or more below the surface. Moisture determinations at twelve different time periods showing the decrease in moisture content after irrigation in each of the three plats, *A*, *B*, and *C*, are presented graphically in Fig. 117, in which the moisture content is plotted against time. The data are prepared in acre-inches of water per acre, for different depths of soil. Observations were made at irregular intervals from June 16 to October 11, there being 2556 determinations, of which 1476 were made in June, 468 in July, and 216 in August and September. The location of borings was systematically determined, and stakes were placed in each hole as soon as the sample had been obtained and the excess disturbed soil had been replaced. On each stake the date of sampling was marked, thus avoiding duplication in the location of borings.

On June 16, immediately after the irrigation water disappeared from the surface of the soil, a straw mulch 8 to 10 in. deep was spread over the surface. To determine the loss of water through the straw, an evaporimeter pan 12 in. by 20 in. was filled with soil of about the same moisture content as that in the plat and placed under the straw in plat *A* with its surface flush with the ground surface. From August 2 to 26 the pan lost 0.383 cm depth, or 0.035 cm a day. The decrease in

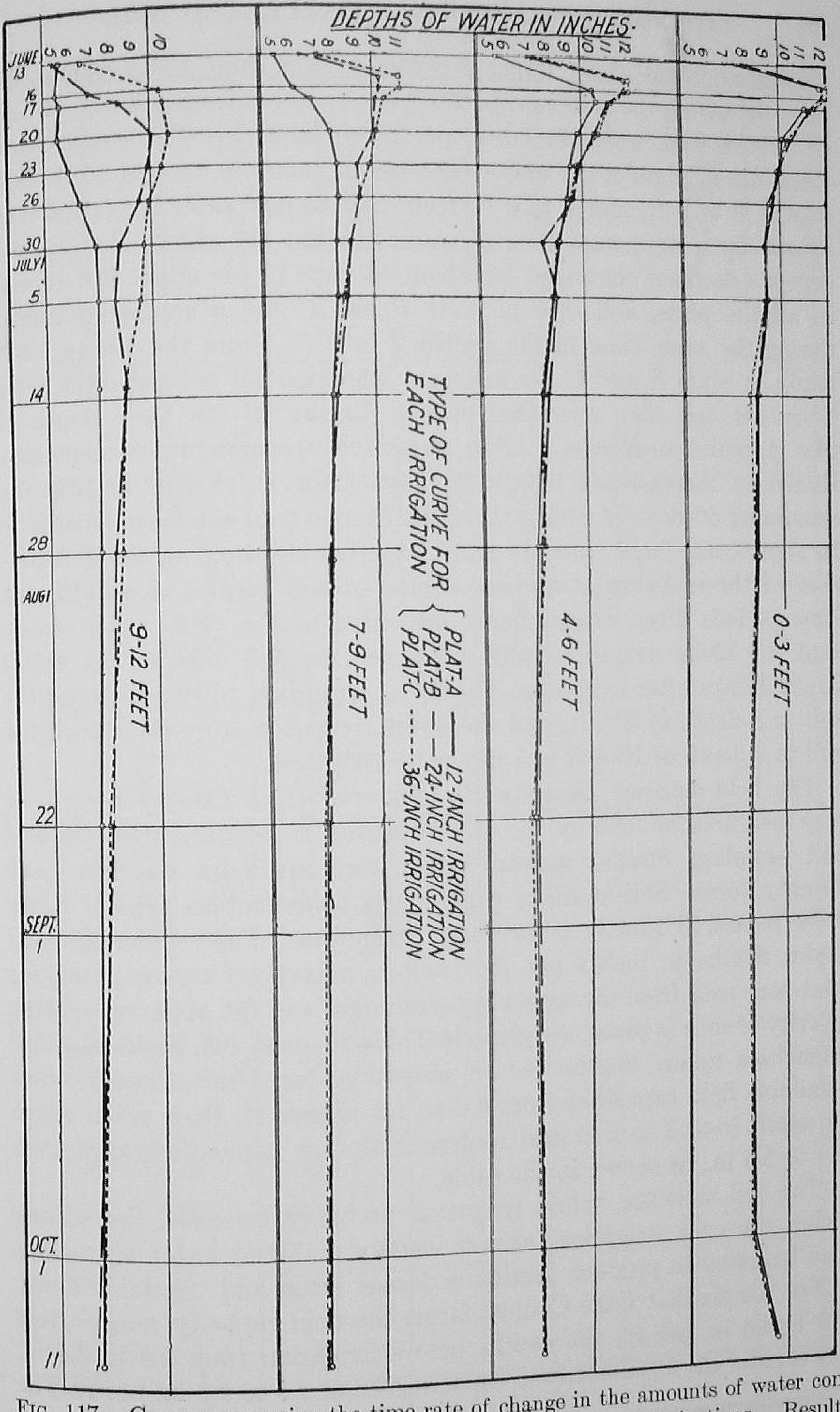


FIG. 117. Curves comparing the time rate of change in the amounts of water contained in the same depths of soil after each of three different irrigations. Results are expressed in inches depth of water in each of the four depths of soil considered. (Calif. Agr. Exp. Sta., *Hilgardia*, Vol. 2, No. 14.)

moisture content of the upper 6 ft of soil from June 16 to August 22, after deducting the water evaporated, shows losses from plats A, B, and C of 0.58, 0.64, and 0.71 cm respectively, in 24 hr. The evaporation losses are negligible; the major decrease in moisture content of the soil depths, 0 to 3 ft, and 4 to 6 ft, from day to day after irrigation was caused by a downward flow of water. Figure 117 shows that a perceptible decrease continued for about 15 days in the upper 6 ft of soil in all the plats, and that in plats B and C the decrease continued during the same time in the depths 7 to 9 ft. From the 10- to 12-ft depth in plats B and C the moisture increased for several days after irrigation and then decreased slowly. In the 10- to 12-ft depth of plat A, which was given a 12-in. irrigation, the moisture content continued to increase for nearly 20 days after irrigation. During the remaining 50 days of observation the change was not large enough to be significant. Data from the same experiments showing the distribution of the moisture at various depths of soil in plat A at different time periods after irrigation are presented in Fig. 118, which shows that the 12-in. irrigation fully moistened the soil only to the 4½-ft depth 2 days after irrigation. The 24-in. irrigation fully moistened the soil to a depth of 8½ ft, and the 36-in. irrigation fully moistened the soil to a depth of 10½ ft in 1 day after irrigation.

The field-moisture capacity P_{fc} of eleven Utah County farm soils was measured in 1942 by the direct method of ponding, flooding, and soil sampling. Similar measurements were made on six Salt Lake County farms. Soil-moisture percentages on seventeen typical farms were measured shortly before each irrigation.* Field capacities and water depths in inches per foot before irrigation, as computed for root-zone soils from the moisture percentages and the apparent specific gravity of soils in place, are given in Table 24, page 206. Field-moisture capacities minus depths before irrigation for Utah County show available field capacities from 0.6 to 1.2 in. per ft. Root zones range in depth from 3 to 5 ft and root-zone storage capacities range from 2.4 to 5.5 in., as shown in the table.

The soil moisture before irrigation probably exceeded the wilting point, since the irrigation farmers usually obtained water on request and irrigated to produce maximum forage grain and vegetable crops.

For the six Salt Lake County farms the field capacity ranged from 2.6 to 4.6 in. per ft; the depths before irrigation from 2.0 to 3.5 in. per ft; and the available field capacities from 0.6 to 1.6 in. per ft. The

* During these studies, each farm was irrigated several times, and 145 sets of moisture determinations were made to find the average moisture content of the root-zone soil before 145 irrigations.

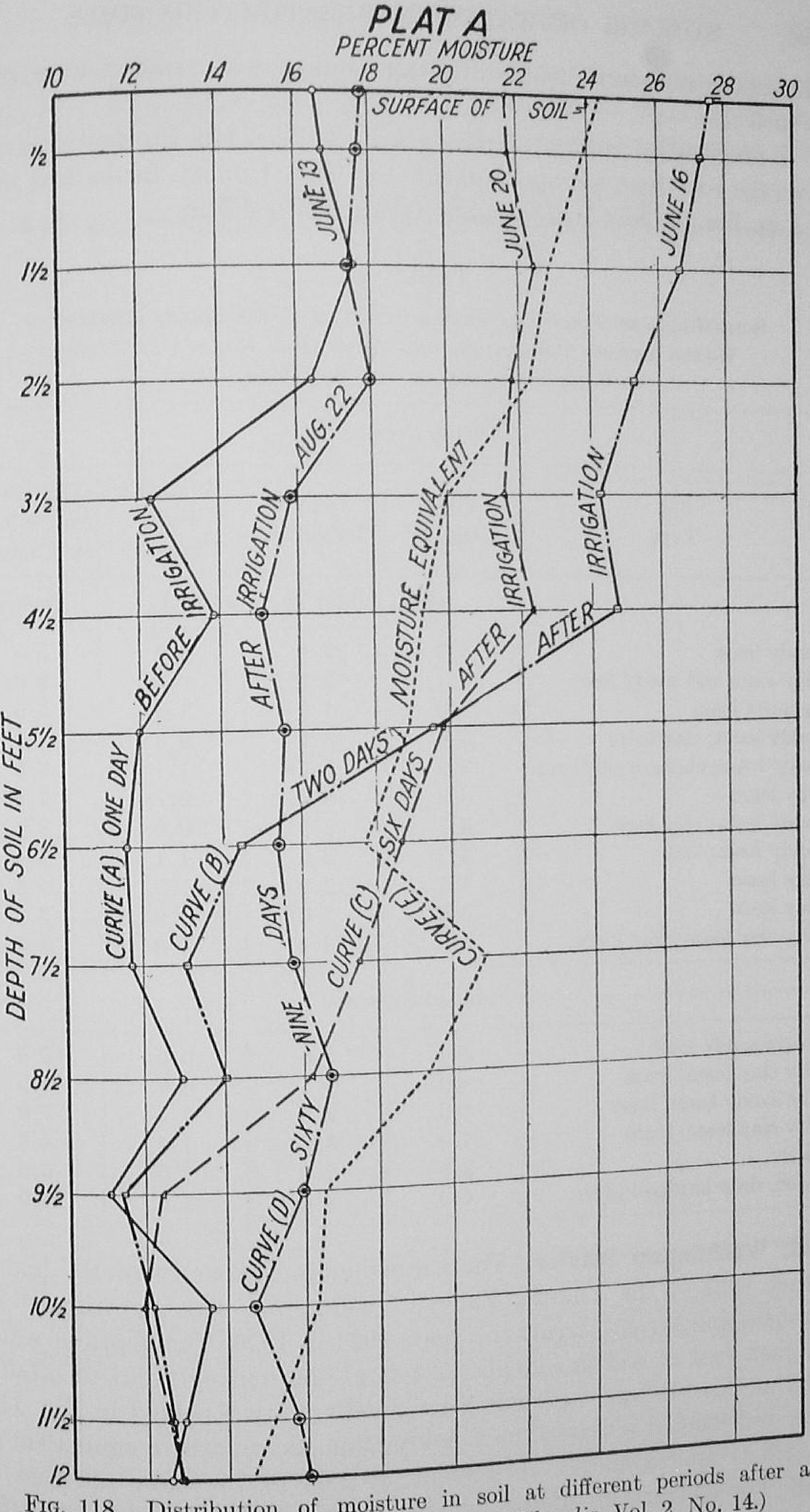


Fig. 118. Distribution of moisture in soil at different periods after a 12-in. irrigation. (Calif. Agr. Exp. Sta. *Hilgardia*, Vol. 2, No. 14.)

maximum root-zone depths of Utah County soils studied were from 3 to 5 ft.

A noteworthy feature of the data in Table 24 is the fact that the average root-zone storage capacity for Utah County farms was only 4.1 in. For the Salt Lake County farms it was 5.3 in.

TABLE 24

Soil-Moisture Field Capacities of Utah Farm Soils, Depths of Water before Irrigation, and Available Field Capacities in Each Foot and in the Soil-Root Zone

Soil Type	Field Capacity	Before Irrigation	Available Field Capacity	Root-Zone Water-Storage Capacity
	Inches Water per Foot Soil			Inches
Utah County				
Sandy loam	3.3	2.1	1.1	5.5
Clay loam and sandy loam	3.1	2.3	0.8	4.0
Gravelly loam	3.0	1.9	1.1	5.5
Sandy loam; clay loam	3.9	3.1	0.8	4.0
Sandy loam; clay gravelly loam	3.2	2.1	1.1	5.5
Clay loam	3.8	3.1	0.7	3.5
Sandy loam; clay loam	3.1	2.5	0.6	3.0
Sandy loam; clay	4.7	3.6	1.1	4.4
Clay loam	4.1	2.9	1.2	4.8
Clay loam	3.9	3.0	0.9	2.7
Silty clay loam; clay loam	4.0	3.4	0.6	2.4
Salt Lake County				
Coarse sandy loam	2.6	2.0	0.6	3.0
Silty clay loam; loam	4.0	3.1	0.9	4.5
Fine sandy loam; loam	4.0	2.6	1.4	7.0
Silty clay loam; loam	4.6	3.5	1.1	4.4
Loam	3.8	2.8	1.0	5.0
Loam, deep hardpan phase	4.0	2.4	1.6	8.0

145. Washington Studies The water-holding capacity of the higher bench soils of the Yakima Valley, Washington, was investigated by Scofield and Wright during the years 1924 to 1926. The depth of water in each foot of soil to a depth of 4 ft at the wilting point of alfalfa, and at three different periods after flooding, are reported in Fig. 119. The soil studied is classed as a sandy loam, the moisture equivalent of which is approximately 16 percent, or 2.65 in. of water per foot of soil. For conversions of the moisture percentages to inches of water

per foot of soil, the apparent specific gravity of the soil was assumed to be 1.38. It is noteworthy that the field capacities reported for the several depths of the Yakima Valley soils assume a condition of sub-

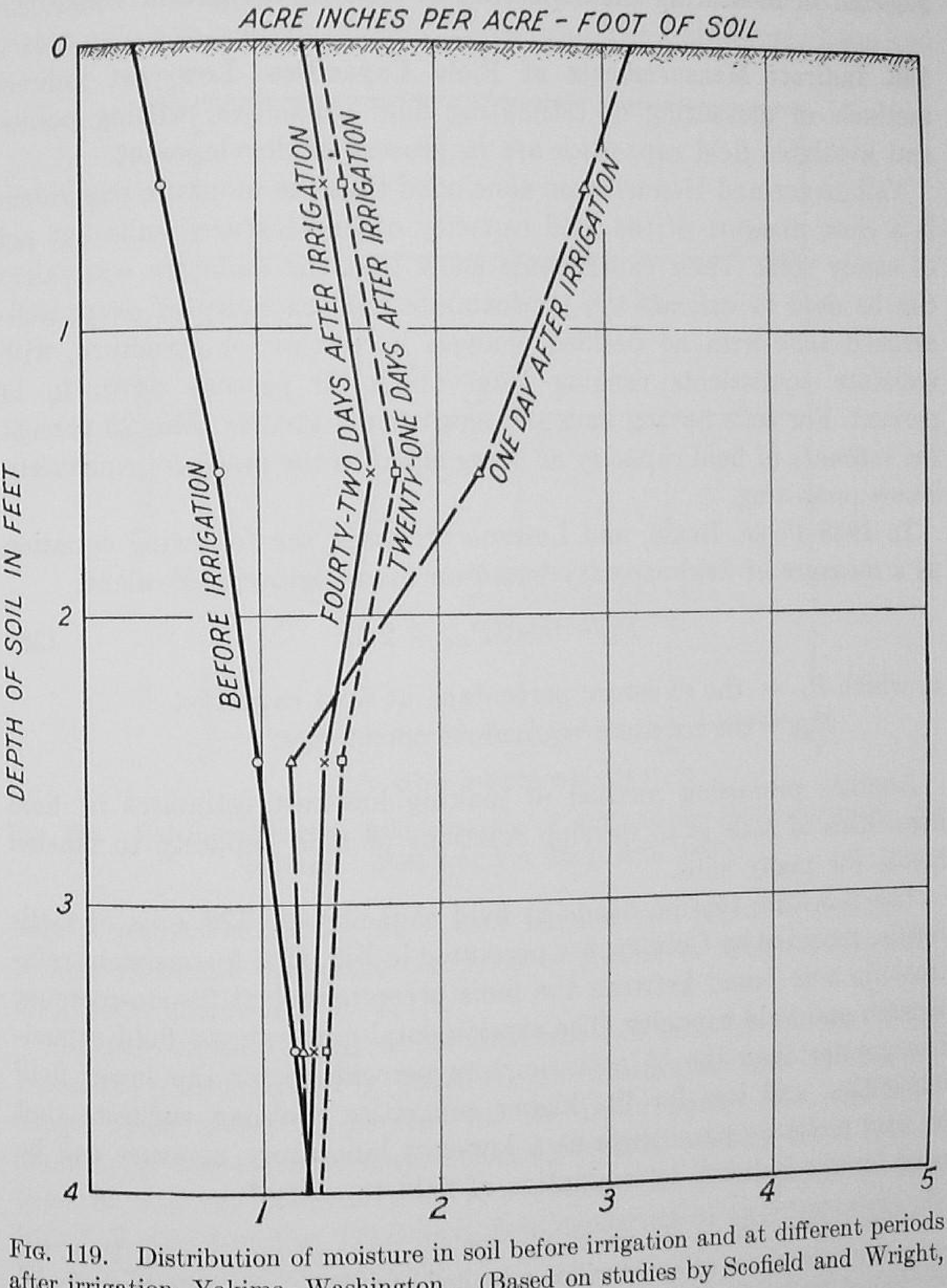


FIG. 119. Distribution of moisture in soil before irrigation and at different periods after irrigation, Yakima, Washington. (Based on studies by Scofield and Wright, *J. Agr. Research*, Vol. 37, No. 2.)

stantial equilibrium 24 hr after irrigation. However, the moisture tests at the later periods show that an appreciable amount of water moved downward into the third and fourth foot sections after the observations

1 day following irrigation. This fact would seem to support the conclusion stated above that the time period after flooding which represents the field capacity is difficult to determine and must be arbitrarily selected in measuring the capacities of soils for irrigation water.

146. Indirect Measurements of Field Capacities Low-cost indirect methods of measuring or estimating field capacities, wilting points, and available field capacities are in process of development.

Veihmeyer and Hendrickson concluded that the moisture equivalent is a close measure of the field capacity of fine-textured soils but not of sandy soils. Their experiments show that the moisture equivalent can be used to indicate the approximate field capacity of deep, well-drained soils with no decided changes in texture or structure, with moisture equivalents ranging from about 30 percent down to 14 percent. For soils having moisture equivalents greater than 20 percent the *estimate* of field capacity as being equal to the moisture equivalent seems promising.

In 1948 Peele, Beale, and Lesesne proposed the following equation as a measure of field capacity based on the moisture equivalent:

$$P_{fc} = 0.865P_{me} + 2.62 \tag{36}$$

in which P_{fc} = the moisture percentage at field capacity.
P_{me} = the moisture equivalent percentage.

Another promising method of making low-cost estimates of field capacities of soils is to develop relations of field capacity to tension heads for many soils.

The moisture tension heads at field capacity for 120 soils of California, reported by Colman, are presented in Fig. 120. A consistent relationship was found between the moisture retained at 25-cm-mercury tension and field capacity. The experimental curve shows field capacities greater than the ⅓ atm moisture percentage for the lower field capacities, and less for the higher capacities. Colman suggests that ⅓ atm moisture percentage as a low-cost laboratory measure can be used for the indirect determination of field capacity.*

* Two precautions in the use of Fig. 120 are proposed by Colman: First, the curve represents soils collected within a limited area. Soils in other regions should be studied by the method described. Second, it represents young or immaturely developed free-draining soils in which the water table is so far below the layer under consideration that it exerts no influence upon the drainage of that layer. The curve would not be expected to hold for soils in which the water table is only a few feet below the surface, or those in which drainage is impeded by a horizon of very low permeability.

The relations of soil-moisture content to tension from five California soils reported by Richards are presented in Figs. 121*A* and 121*B*.

The moisture tension, reported in atmospheres, for olympic clay increased from 1 atm with a 41 percent moisture content to 20 atm with a moisture content of about 23 percent. The Indio sandy loam had

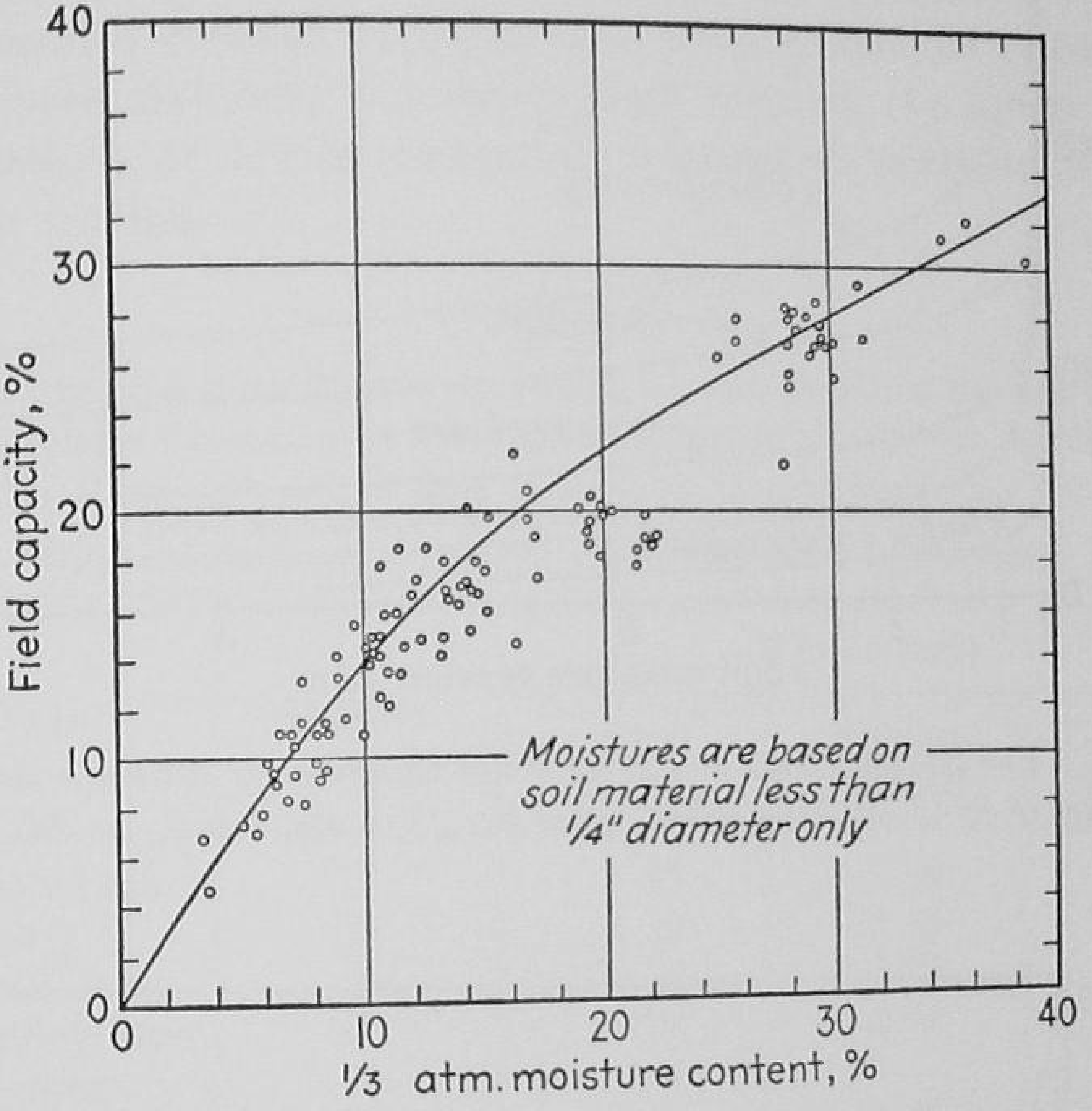


FIG. 120. Relation between field capacity of soil and its ⅓-atm moisture percentage. (*Soil Sci.*, Vol. 63, p. 280, 1947.)

only 5 percent moisture at 1 atm tension and about 2 percent at 20 atm. Students can make comparisons similar to these for the other three soils, shown in Fig. 121*A*.

Moisture-tension relations for the same five soils for tensions below 1 atm are presented in Fig. 121*B*. At zero tension the moisture content ranges from about 32 percent for the Indio sandy loam up to 80 percent for the olympic clay. Selecting ⅓ atm tension (or a tension head of 345 cm of water) as representing the field capacity, then soils 1, 2, and 3 of Fig. 121*B* have field capacities of approximately 46, 32, and 25 percent respectively.

The field capacity depends in part on the initial moisture distribution, the moisture-transmitting properties of the soil, its moisture-retaining properties, and the depth of water applied. It is, therefore, difficult to base a field-capacity estimate on disturbed soil samples. However, to facilitate progress toward increasing water-application

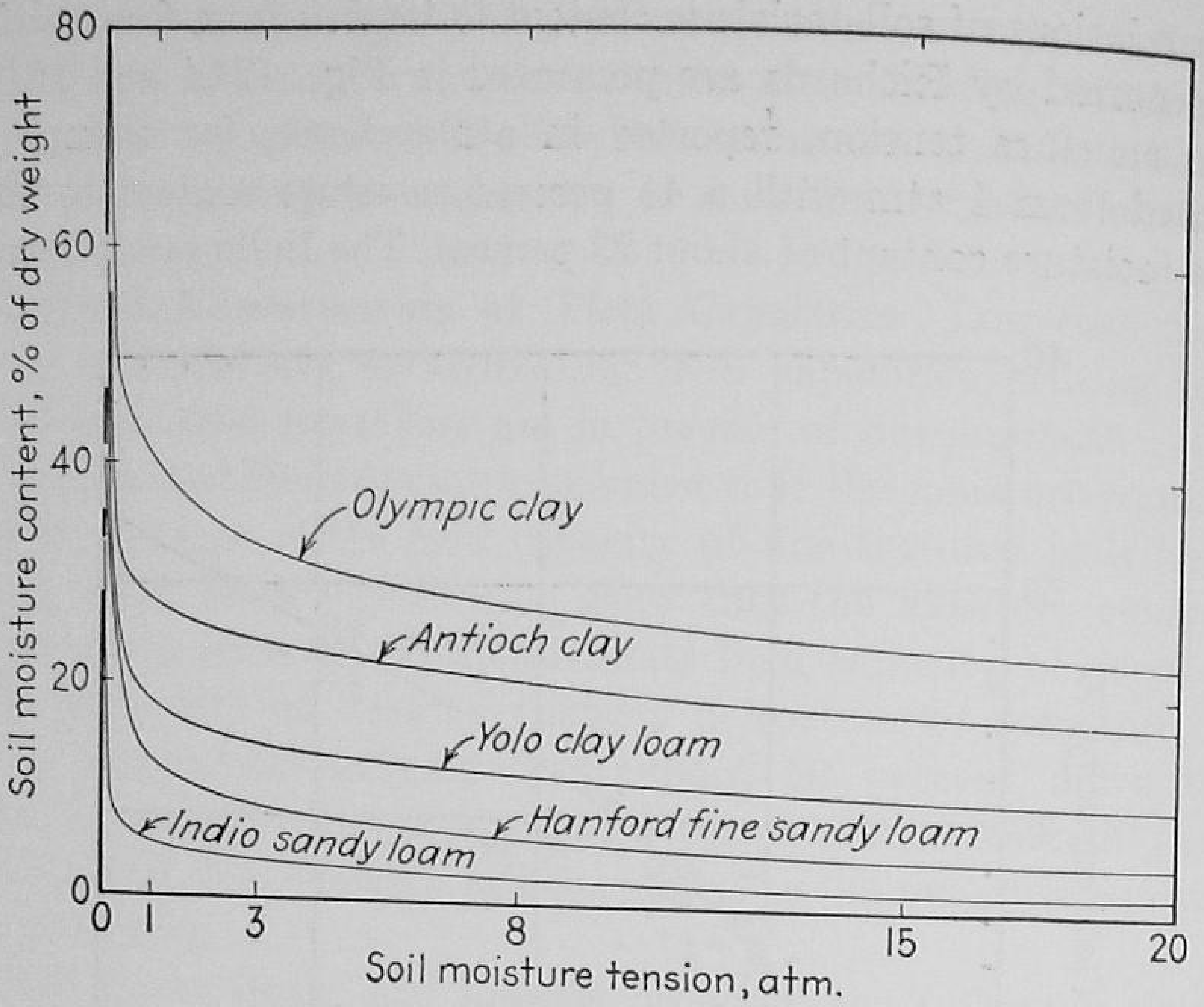


FIG. 121*A*. The 20-atm range of soil-moisture tensions for different moisture percentages of five California soils. (*Soil Sci.*, Vol. 68, No. 1, p. 105, 1949.)

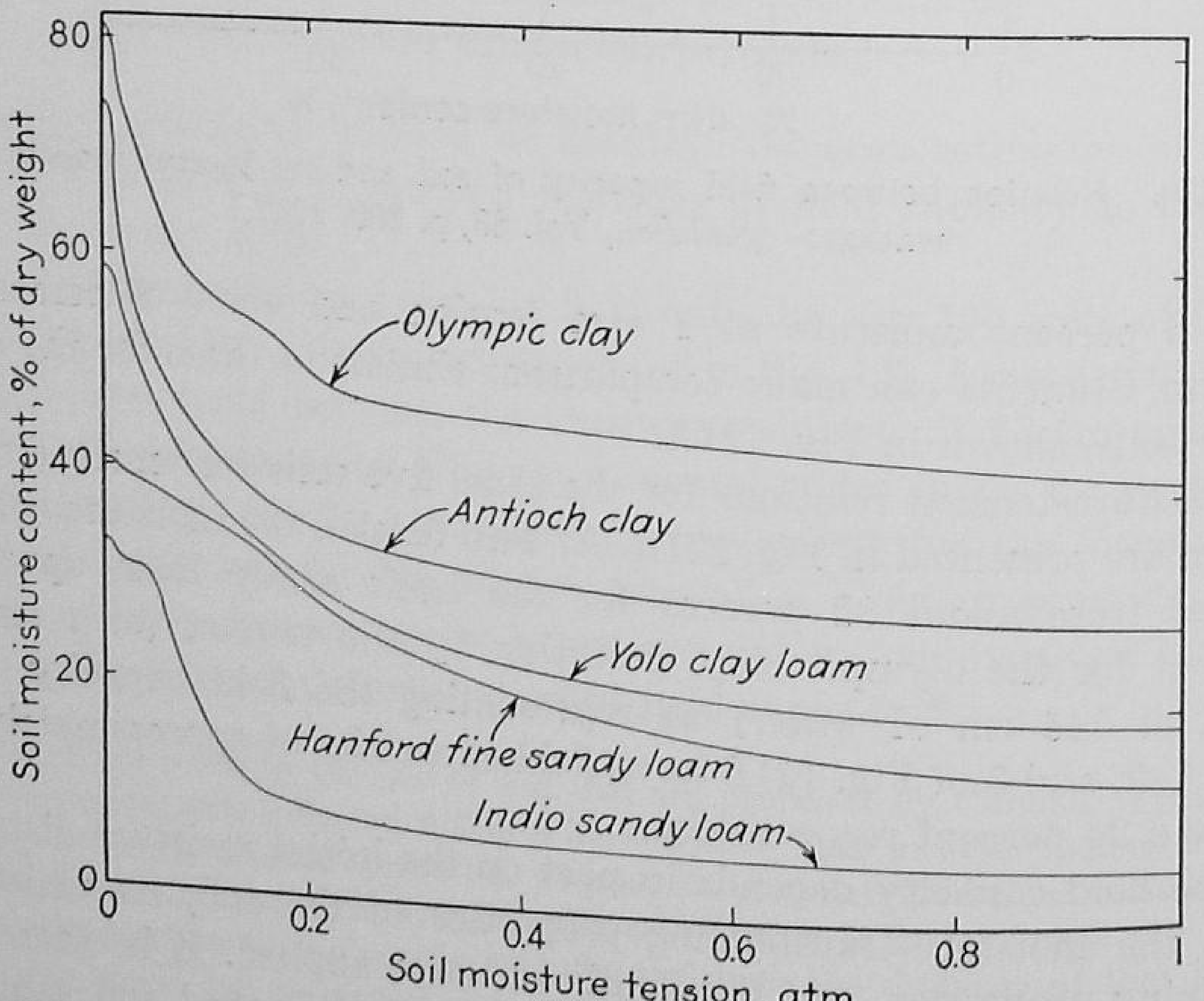


FIG. 121*B*. The 1-atm range of soil-moisture tension for different moisture percentages of five California soils. (*Soil Sci.*, Vol. 68, No. 1, p. 106, 1949.)

efficiencies, it is essential to develop low-cost methods of estimating field capacities, wilting points, and *available* water capacities.

147. Permanent Wilting Points Direct measurements of the wilting percentage of soils by growing plants are time-consuming and costly. Indirect methods, urgently needed, are being developed.

The moisture content at permanent wilting may be estimated by either of three methods: (*a*) direct plant method, (*b*) direct moisture tension method, or (*c*) by computation based on moisture percentage at a given tension.

TABLE 25

PERMANENT WILTING POINTS OF SOUTH CAROLINA SOILS BY THE PLANT METHOD COMPARED WITH PERCENTAGES OF MOISTURE AFTER PRESSURE OF 15 ATM AND WITH CALCULATED P_{wp}

(Unpublished data courtesy of Soil Conservation Service)

Soil Type	Horizon	Wilting Point		
		Plant Method	Pressure Method*	Calculated Percent†
Norfolk sandy loam	*A*	1.65	1.06	2.02
Norfolk sand	*A*	1.77	1.14	2.10
Dunbar sandy loam	*A*	2.21	1.51	2.46
Marlboro sandy loam	*A*	2.94	2.60	3.52
Lynchburg sandy loam	*A*	3.54	2.22	3.15
Wickham sandy loam	*A*	3.81	2.84	3.75
Lynchburg sandy loam	*B*	5.68	4.23	5.10
Cecil sandy loam	*A*	6.33	5.50	6.34
Iredell silt loam	*A*	6.41	5.83	6.66
Norfolk sandy loam	*B*	7.46	6.71	7.52
Georgeville silt loam	*A*	7.69	5.74	6.57
Dunbar sandy loam	*B*	7.89	6.58	7.39
Marlboro sandy loam	*B*	10.22	9.64	10.37
Cecil clay loam	*A*	10.62	10.44	11.15
Lloyds clay loam	*A*	12.51	11.90	12.57
Davidson clay loam	*A*	17.58	17.45	17.97
Wickham silt loam	*B*	18.35	17.48	17.99
Lloyds clay loam	*B*	19.43	19.42	19.88
Davidson clay loam	*B*	22.79	21.24	21.65
Iredell silt loam	*B*	23.04	23.49	23.84
Georgeville silt loam	*B*	24.39	23.90	24.24

* Percent water, oven-dry basis, retained at equilibrium with 15-atm pressure over a cellophane membrane.

† Calculated from equation 37.

The plant method requires from 2 to 3 weeks and is too expensive to be widely used. The indirect tension method cost is only a fraction of the plant method cost. Peele and colleagues report that six tension-wilting-point determinations can be made in one 24-hour day. Their results of wilting-point determinations by each of these three methods on 21 soils, previously mentioned, are presented in Table 25.

The equation used for the computation method is

$$P_{wp} = 0.97P_{15} + 0.99 \tag{37}$$

in which P_{wp} = the permanent wilting percentage.

P_{15} = the percentage at 15-atm tension.

The mean difference between the wilting points calculated from the 15-atm moisture percentages by means of equation 37 and the wilting points determined by the plant method was 0.41 percent water. Replicates by the pressure method were less variable than replicates by the plant method.

148. Available Water Capacities Using equation 36 to find the field capacities of soils based on moisture-equivalent determinations and the wilting point, and the wilting-point tests reported in Table 25, Peele

TABLE 26

WATER REQUIRED TO RAISE THE SOIL-MOISTURE CONTENT FROM THE WILTING POINT TO THE FIELD CAPACITY WHICH IS THE AVAILABLE WATER-HOLDING CAPACITY, SURFACE INCHES

(*Agr. Engr.*, Vol. 29, p 158)

Soil Type	Depth of Soil Zone, Feet			
	0–1	0–2	0–3	Average per Foot for Upper 3 Ft
Dunbar fine sandy loam	1.61	3.02	4.44	1.48
Charleston loamy fine sand	1.11	2.01	2.91	0.97
Leaf silt loam	2.04	3.22	4.41	1.47
Stono loam	1.91	3.19	4.47	1.49
Weston fine sandy loam	1.48	3.21	4.95	1.65
Portsmouth loam	2.27	3.29	4.56	1.52
Coxville fine sandy loam	1.16	2.32	3.48	1.16
Grady loam	1.52	3.96	4.59	1.53
Bladen fine sandy loam	1.00	2.66	4.53	1.51
Norfolk sandy loam	0.82	1.96	3.25	1.08
Hayesville sandy loam	1.27	2.68	4.11	1.37
Cecil sandy loam	1.59	3.13	4.76	1.59

and associates have computed available or usable water-holding capacity in terms of the depth of water required at each irrigation to add to the soil its available capacity, in each foot of soil of the 3-ft root zone. Results of their determinations of available water-holding capacity by this method, as presented in Table 26, show that the available capacity of 12 soil types ranged from 0.82 to 2.27 in. of

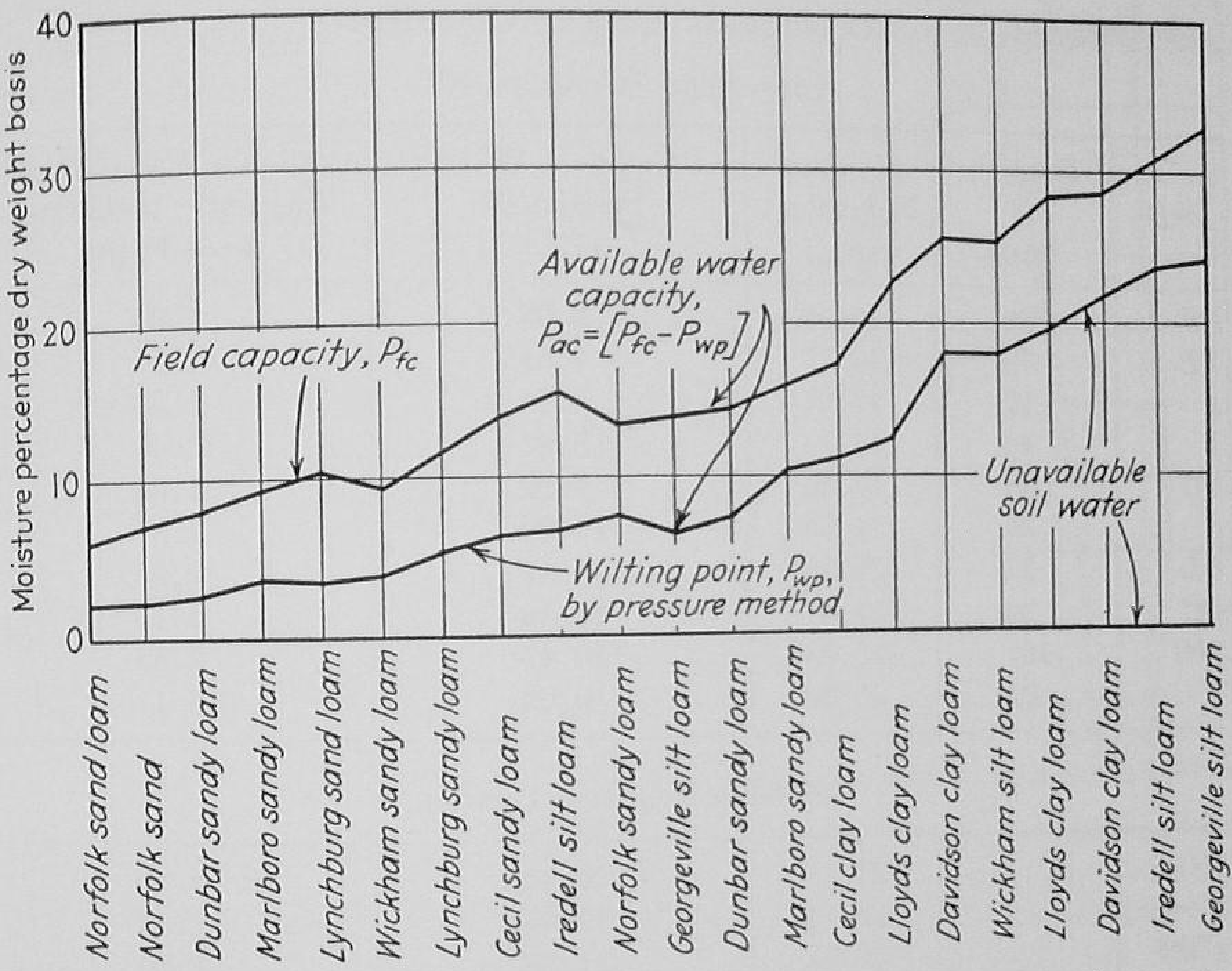


FIG. 122. Field-moisture capacity, wilting point, and available capacity for twenty-one South Carolina soils. (Unpublished data based on studies by T. C. Peele, O. W. Beele, and F. F. Lesesne.) (Courtesy Soil Conservation Service.)

water for the 1-ft depth of soil, 1.96 to 3.29 in. for the 2-ft depth, and 2.91 to 4.95 in. for the 3-ft depth. The last column of Table 26 shows that the average available water-holding capacity for the upper 3 ft ranged from 0.97 to 1.65 in. per ft. The need for and the advantages of supplemental irrigation of these South Carolina soils is evident by the limitations of the root zone to store available water.

The influence of the texture of soils on the field capacity, 15-atm percentage (approximate wilting point), and available capacity is illustrated by the data of Fig. 122. The sandy soils have only small amounts of unavailable water, 5 percent or less, whereas some of the silt loams and clay loams have 20 percent or more.* The ratio of

* Dunbar sandy loam and some others listed twice represent soils of different horizons *A* and *B*.

available capacity P_{ac} of the Norfolk sand to the wilting point P_{wp} is greater than 3, whereas the same ratio for the Lloyds clay loam is less than 0.5. Knowledge of the moisture properties of different soils is essential to irrigation progress.

TABLE 27

Some Soil Moisture Relations for Typical Agricultural Soils in California

(*Agr. Eng.*, Vol. 18, p. 249)

Soil	Number of Trials	Moisture Equivalent (P_{me})	Permanent Wilting Percentage (P_{wp})	Available Water-Holding Capacity, Inches per Foot Depth
FS	226	10.50	3.08	1.24
TL	78	13.71	4.51	1.54
J	17	17.07	6.14	1.83
Y	40	17.16	8.82	1.40
TC	24	17.30	7.89	1.58
S	39	21.35	10.20	1.87
OL	27	23.36	6.12	2.89
OC	29	24.51	11.55	2.17
MG	151	25.63	10.47	2.54
V	24	37.90	19.03	3.17
Paradise Irrigation District				
*P*1–1	...	33.33	20.45	1.70
*P*1–2	...	29.74	19.66	1.43
*P*1–3	...	30.51	21.38	1.20
*P*1–4	...	32.21	23.47	1.15
*P*1–5	...	31.19	23.09	1.07
*P*4–1	...	31.45	19.50	1.57
*P*4–2	...	29.01	19.87	1.20
*P*4–3	...	28.14	20.12	1.06
*P*4–4	...	27.66	21.28	0.84
*P*4–5	...	27.73	22.05	0.75

Studies of water-storage capacity by indirect methods reported by Edlefsen for ten typical agricultural soils of California show available capacities ranging from 1.24 to 3.17 in. per ft. The moisture-equivalent percentages of these soils, as shown in Table 27, range from 10.50 to 37.90 and the wilting percentage from 3.08 up to 19.03. Table 27, based on 655 trials, shows also available moisture capacities per foot depth of soil for Paradise Irrigation District soils at two of the twelve locations. The depths range from 1.70 in. for the first foot depth at location P_1 to 0.75 in. for the fifth foot at a location P_4. The un-

available and the available soil water for each foot of soil down to a depth of 5 ft for one of the Paradise Irrigation District soils is presented also in Fig. 123.

Direct and indirect measurements of available water capacities are helpful in irrigation practice. Estimates of available capacities of different soils may be used where measurements are not available. McCulloch's estimates for seven classes of soils of different texture and profile are presented in Table 28. The depths of irrigation water required, under 100 percent water-application efficiency (see Article 150), for root-zone soil depths of 2 ft, 4 ft, and 6 ft are also presented in Table 28. For 2-ft soil depth the estimated water depth ranges from 1 to 3.2 in.

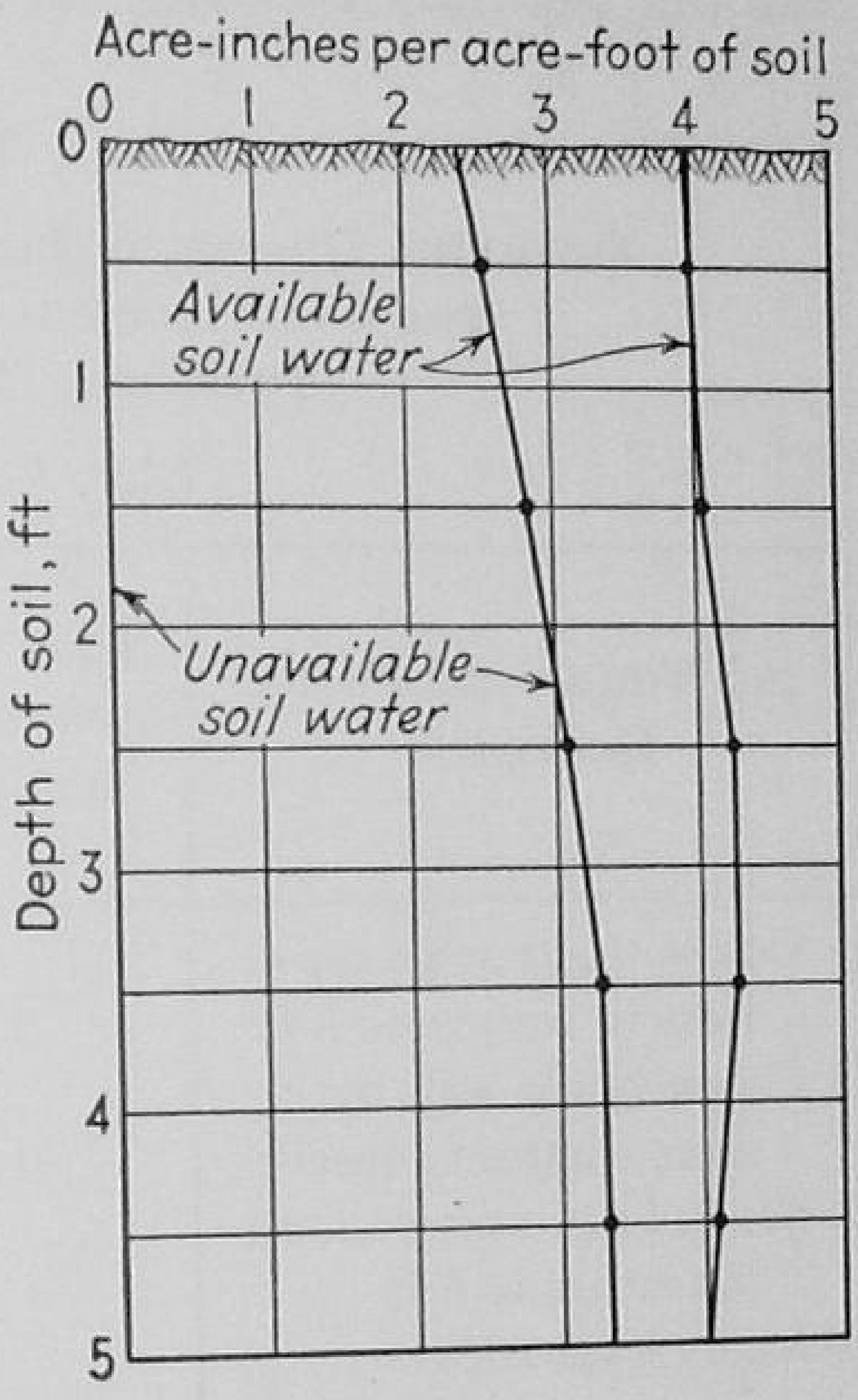


FIG. 123. Available and unavailable moisture in the upper 5 ft of one California soil as determined by Edlefsen. (*Agr. Eng.*, Vol. 18, p. 247, 1937.)

149. Filling the Available Soil-Water Reservoir Equation 30 of Chapter 6 shows that

$$da = qt$$

By interpreting the depth d of this equation as the depth of water necessary to spread uniformly over the land surface in order to fill the capillary reservoir, or satisfy the field capacity, of the soil to a given depth, then the d of equation 35 is equivalent to the d of this equation. It therefore follows, by comparison of the two equations, that

$$\frac{qt}{a} = \frac{P_{ac}A_sD}{100}$$

from which it is apparent that

$$t = \frac{P_{ac}A_sDa}{100q} \qquad (38)$$

Provided the apparent specific gravity A_s is known, it is possible to compute the hours required to add a given moisture percentage P_{ac} to a field of given area a and a soil of certain depth D when using a stream of water of q cfs (acre-inches per hour).

Equation 38 may, for example, be used with values of P_{ac}, which represent moisture at field capacity of the soil minus the moisture content before irrigation. Veihmeyer and associates have found, working with some California soils, that it is impracticable to add to great depths of soil small percentages of water in the capillary form, since the full capillary capacity for water of the surface soil must be satis-

TABLE 28

ESTIMATED DEPTHS OF IRRIGATION WATER IN INCHES TO FILL THE AVAILABLE STORAGE CAPACITIES OF SOILS OF DIFFERENT TEXTURE AND PROFILE

(*Agr. Eng.*, Vol. 30, p. 24)

Soil Texture and Profile Description	Total Soil Moisture Capacity for Plant Use, inch per ft depth	Soil Moisture to Replace per Irrigation for 2-, 4-, and 6-ft Root-Zone Soil, inches		
		2-ft	4-ft	6-ft
1 Coarse sandy soils, uniform in texture to 6 ft	0.50–0.75	1.0	1.75	2.5
2 Coarse sandy soils over more compact subsoils	0.75–1.00	1.5	2.0	3.0
3 Sandy loam soils uniform in texture to 6 ft	1.25–1.50	2.0	3.0	4.7
4 Sandy loam soils over more compact subsoils	1.25–1.75	2.2	3.2	5.0
5 Silt loam soils uniform in texture to 6 ft	1.75–2.25	3.0	4.0	6.5
6 Silt loam soils over more compact subsoils	2.00–2.25	3.2	4.2	6.7
7 Heavy-textured clay or clay loam soils	1.80–2.00	2.5	3.2	5.5

fied before the water moves to lower depths. Likewise, it is very difficult to spread water uniformly over the land.

Keeping these factors in mind, equation 38 has practical utility. To simplify the use of equation 38, Table 29 has been prepared. It applies directly only to soils having an apparent specific gravity of $A_s = 1.4$. For soils having higher or lower values of A_s, proportional corrections must be made. The use of Table 29 is illustrated by the following example: An irrigator has at his disposal a stream of 3 cfs and he wants to apply enough water to increase the 4-ft-depth root-zone soil moisture from 10 percent to 15 percent. How many hours will be required if the water is spread uniformly and losses are neglected? Column 6 of Table 29 shows that 0.28 hr is required to supply enough

TABLE 29

TIME IN HOURS t REQUIRED WITH A STREAM q TO ADD VARIOUS PERCENTAGES OF AVAILABLE MOISTURE P_{ac} TO 1 ACRE-FOOT OF SOIL, THE APPARENT SPECIFIC GRAVITY OF WHICH IS 1.4 BASED ON $t = \frac{P_{ac}A_sDa}{100q}$

Col. No.		1	2	3	4	5	6	7	8	9	10
Line No.	Available Capacity (P_{ac})	Size of Stream, q cfs									
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
1	4.0	1.34	0.67	0.45	0.34	0.27	0.22	0.19	0.17	0.15	0.13
2	4.2	1.41	.71	.47	.35	.28	.24	.20	.18	.16	.14
3	4.4	1.48	.74	.49	.37	.29	.25	.21	.18	.16	.15
4	4.6	1.55	.77	.52	.39	.31	.26	.22	.19	.17	.15
5	4.8	1.61	.81	.54	.40	.32	.27	.23	.20	.18	.16
6	5.0	1.68	.84	.56	.42	.34	.28	.24	.21	.18	.17
7	5.2	1.75	.87	.58	.44	.35	.29	.25	.22	.19	.17
8	5.4	1.81	.90	.60	.45	.36	.30	.26	.23	.20	.18
9	5.6	1.88	.94	.63	.47	.37	.31	.27	.23	.21	.19
10	5.8	1.95	.97	.65	.49	.39	.32	.28	.24	.22	.19
11	6.0	2.02	1.01	.67	.50	.40	.34	.29	.25	.22	.20
12	6.2	2.08	1.04	.69	.52	.42	.35	.30	.26	.23	.21
13	6.4	2.15	1.08	.72	.54	.43	.36	.31	.27	.24	.22
14	6.6	2.22	1.11	.74	.55	.44	.37	.32	.28	.24	.22
15	6.8	2.29	1.15	.76	.57	.46	.38	.33	.29	.25	.23
16	7.0	2.35	1.17	.78	.59	.47	.39	.34	.29	.26	.23
17	7.2	2.42	1.21	.81	.60	.48	.40	.35	.30	.27	.24
18	7.4	2.49	1.25	.83	.62	.50	.41	.36	.31	.28	.25
19	7.6	2.56	1.28	.85	.64	.51	.42	.36	.32	.28	.26
20	7.8	2.62	1.31	.87	.65	.52	.44	.37	.33	.29	.26
21	8.0	2.69	1.35	.90	.67	.54	.45	.38	.34	.30	.27

water with a 3-cfs stream to add 5 percent moisture to 1 acre-foot of soil. Therefore, in 1.12 hr, enough water is applied to add 5 percent moisture to 4 acre-feet of soil, and longer application is likely to result in deep percolation loss provided the 5 percent satisfies the field capillary capacity for usable or available water, or fills the capillary reservoir.

150. Water-Application Efficiency Water-application efficiency is defined as the ratio of the volume of water that is stored by the irrigator in the soil root zone and ultimately consumed (transpired or evaporated, or both) to the volume of water delivered at the farm.

The need for increasing water-application efficiencies in irrigation justifies careful consideration of the factors that influence them, even though some are not easily measured. High water-application efficiencies increase the probability that water will be economically used, although efficiencies, as here defined, involve neither water costs nor crop yields or values.

Let E_a = water-application efficiency.
W_f = irrigation water delivered to the farm.
W_s = irrigation water stored in the root zone of soil of the farm.

Then by definition

$$E_a = \frac{100W_s}{W_f} \tag{39}$$

Common sources of loss of irrigation water from the farm during application are represented thus:

R_f = surface runoff from the farm

D_f = deep percolation below the farm root-zone soil

Neglecting the evaporation losses during the time of the application of the water, and immediately after, it follows that

$$W_f = W_s + R_f + D_f \tag{40}$$

Therefore

$$E_a = 100\left[\frac{W_f - (R_f + D_f)}{W_f}\right] \tag{41*}$$

At each irrigation the farmer applies to his land a given volume of water. His irrigation problem is to store this water in the form of soil moisture in the root zone of his soil. He cannot store all the water as soil moisture, for some loss of water is unpreventable. If he stores in his root-zone soil the maximum percentage of the water that he applies, consistent with good irrigation practice and economy, then his water losses are as low as he can reasonably make them. The most common losses of irrigation water are represented by R_f and D_f. Irregular land

* Methods of measuring the volume of water stored in the root-zone soil at each irrigation and the results of measurements on Utah farms as a means of finding E_a are reported in *Utah Experiment Station Bul.* 311.

surfaces, shallow soils underlain by gravels of high permeability, small irrigation streams, non-attendance of water during irrigation, long irrigation runs, excessive single applications—all these factors contribute to a large D_f and a small E_a. Also excessively large heads, improper preparation of land, compact impervious soils, large slope of land surface, and non-attendance contribute to a large R_f and a small E_a. The water depths W_f and R_f can be measured by the farmer at nominal cost, but it is impractical to measure D_f by direct means. In the application of equations 39 and 41 it is essential to measure W_s. The ordinary method of collecting soil samples before and after irrigation and of measuring soil moisture by weighing the soil before and after drying is tedious and costly. The use of tensiometers, described in Chapter 10, for finding the increase in soil-moisture content obtained by each irrigation will facilitate measurement of water-application efficiencies.

151. Some Efficiency Measurements Thirty-nine efficiency E_a tests on one group of Utah farms resulted in an average of 38 percent. Thirty of the tests, or 77 percent, gave an average of less than 50 percent.

The dominant factors contributing to low efficiencies in these 30 irrigations were: excessive applications, 14; uneven distribution of water over the land, 7; excessive moisture content of the soil before irrigation, 5; and combination of these three factors in 4 irrigations. Many factors influence efficiencies in every irrigation.

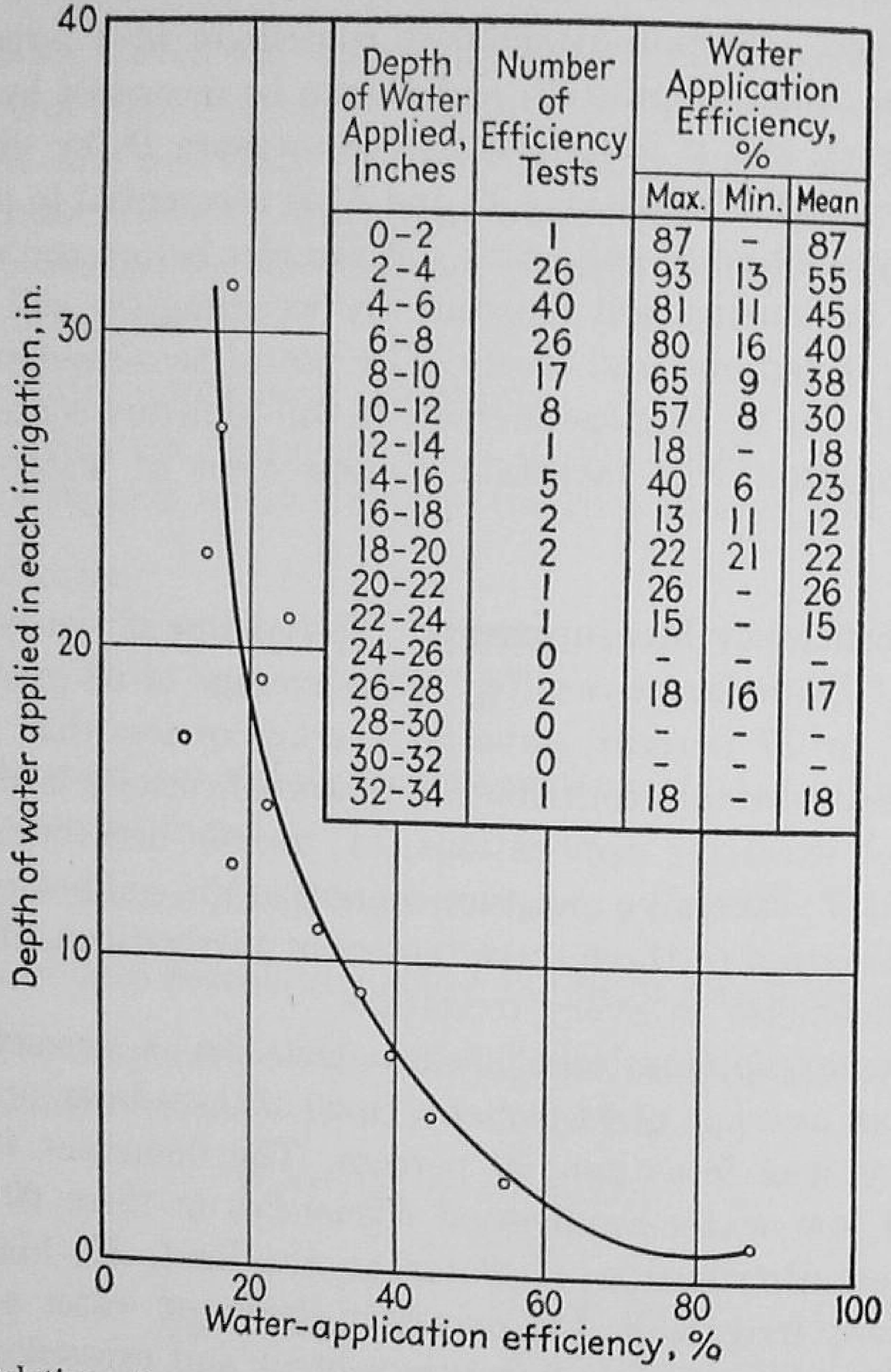
Ninety water-application-efficiency tests on a second group of farms gave an average of 44 percent. In 60 of these tests, or 67 percent, the efficiency was less than 50 percent. The dominant factors contributing to low water-application efficiencies in these 60 irrigations were: uneven distribution of water on the land, 20; high moisture content before irrigation, 15; excessive depth of water applied, 13; and a combination of high moisture content and excessive depth, 12.

Sixteen tests on a third group of farms gave an average of 34 percent. In 12 of these tests, or 75 percent of the total, the water-application efficiency was less than 50 percent. The major factors contributing to low efficiencies were: excessive depths of water applied at each irrigation, spreading the water too far, and irrigating when the soil had considerable moisture and did not need irrigation.

The farms of group one were located near the higher canals of a typical Utah valley on shallow soils of high permeabilities and deep water table. The farms of group two were of medium elevation, having soils of average permeabilities and water tables of average depths. The farms of group three were on the valley lowlands having fine-textured

soils of low permeability. The water table in these soils was from 3 to 5 ft below the ground surface.

Diebold and Williams in 1948 reported measurements of water-application efficiencies in border-strip irrigation and in furrow irriga-



Depth of Water Applied, Inches	Number of Efficiency Tests	Water Application Efficiency, %		
		Max.	Min.	Mean
0-2	1	87	-	87
2-4	26	93	13	55
4-6	40	81	11	45
6-8	26	80	16	40
8-10	17	65	9	38
10-12	8	57	8	30
12-14	1	18	-	18
14-16	5	40	6	23
16-18	2	13	11	12
18-20	2	22	21	22
20-22	1	26	-	26
22-24	1	15	-	15
24-26	0	-	-	-
26-28	2	18	16	17
28-30	0	-	-	-
30-32	0	-	-	-
32-34	1	18	-	18

FIG. 124. Relation of water-application efficiencies to depths of irrigation water applied in each irrigation. (*Utah Agr. Exp. Sta. Bul.* 311.)

tion of New Mexico soil, most of which were clays or clay loams underlain by river sands at depths between 20 and 36 in. They report details of 10 tests in which E_a ranged from 24 to 100 percent, the average for the 10 being 67. In 25 out of 32 irrigations, less than 3 in. of water were stored in the root zone 2 days after irrigation.

152. Depth Water Applied and Efficiency E_a The depth of water applied in each irrigation is a dominant factor influencing E_a. Even if the water were spread uniformly over the land surface, excessive

depths of application would result in low efficiencies. Many variable factors such as land leveling, irrigation method, size of irrigation stream, length of run, soil texture, permeability, and depth influence the time the irrigator keeps water running on his farm and hence the depth he applies. The fact that excessive water depth in each irrigation causes low E_a is shown in Fig. 124, based on 133 Utah tests represented by 14 plotted points.

The curve shows that, when the depth of water exceeded 10 in., the highest E_a was only 30 percent, the lowest 12 percent, and in 5 of the 9 averages plotted it was less than 20 percent.

10

The Flow of Water in Soils

In saturated soils the forces that cause water flow are comparable to the forces that cause flow in pipes; they result from the pull of gravity and from differences in water pressure. The magnitude and directions of these two types of driving forces in saturated soils, as in pipes, can be measured by well-established methods.

In the study of the flow of water in soils, physicists have been primarily interested in unsaturated soils, while geologists and engineers have devoted attention especially to flow in saturated soils. Physicists use the terms: "potentials," "potential gradients," "equipotential regions," "conductivity factors," etc., and engineers use the terms: "hydraulic heads due to pressure and elevation," "hydraulic grade lines (gradients) or slopes," and "hydraulic permeabilities."

In Chapter 10 of the first edition of this book "potentials" and related physical terms were used largely. Because of the trend toward the use of the terms of hydraulic engineering, and because the study of the distribution and flow of water in soils can be simplified by these expressions without loss of clarity, engineering terminology has been adopted in this edition.

It is important to agricultural and engineering students to understand the principles that underlie the control of the flow of water in soils which is essential to economical irrigation and to the prevention of waterlogging of irrigated lands. In a study of this chapter students will find it helpful to review parts of Chapters 4, 8, and 9 and to refer to Table QR, page 21.

Advanced students, of senior college and graduate rank, may with interest review books on fluid mechanics by Rouse, Venard, and others; also books on soil physics by Baver, and on the flow of homogeneous fluids by Muskat.

153. Mechanical Work and Energy Mechanical work is defined as force times distance. To lift 1 lb of water against the force of gravity through a vertical distance of 10 ft requires 10 ft-lb of work.

The principles of mechanical work and energy are applied in the derivation of fundamental formulas for the flow of fluids including the flow of water in soils. Energy is defined as capacity to do work.

In fluids energy may be in three forms:

1. Kinetic energy.
2. Energy resulting from pressure differences.
3. Elevation energy.

A pound of water flowing at a velocity of v feet per second has a kinetic energy of $v^2/2g$ ft-lb, where g is the acceleration of gravity. Also a pound of water at elevation of 100 ft above a given reference or datum plane has elevation energy of 100 ft-lb. A unit of fluid, said to have energy due to pressure differences, has that energy only because of contact with other units of fluid under lower pressures.

154. Energy Equations In fluid mechanics three different unit quantities, namely, force, mass, and volume, are each used for designating the energy of a fluid. The pound is commonly used as the unit of force or weight, the slug as the unit of mass, and the cubic foot as the unit of volume.

The mechanical energy per pound of moving fluid is proportional to the velocity head $v^2/2g$, the pressure head p/w, and the elevation head z, and hence the widely used Bernoulli equation showing energy per unit weight (foot-pounds per pound) is:

$$E_w = \frac{v^2}{2g} + \frac{p}{w} + z = \text{energy per } \textit{unit weight} \text{ of fluid} \qquad \text{(42f)}$$

Remembering that each term of equation 42f is a length L, it follows that, if the equation is multiplied by F/M, each term becomes energy per unit mass or $F\ L/M$. For gravitational force, acceleration $g = F/M$, and each term of the equation

$$E_m = g\left[\frac{v^2}{2g} + \frac{p}{w} + z\right] = \text{energy per } \textit{unit mass}^* \text{ of fluid} \qquad \text{(42m)}$$

Since w is force per unit volume F/L^3, each term of the equation

$$E_v = w\left[\frac{v^2}{2g} + \frac{p}{w} + z\right] = \text{energy per } \textit{unit volume} \text{ of fluid} \qquad \text{(42v)}$$

* Table QR shows also that $g = L/T^2$. The term "potential" is used by some authorities for the energy-per-unit-mass equation. Some authors designate $(p/w + z)$ as potential head.

In the present edition the basic equation 42f for energy *per unit weight* (the pound) has been adopted though previously the basic equation 42m for energy per unit mass was used.

The velocity of ground-water flow, as a rule, is low, and energy due to velocity is negligible and not considered, thus leaving the pressure head p/w and the elevation head z as the basic and important energy elements. The sum of these two is designated as the hydraulic head.

155. Hydraulic Grade Lines and Slopes In engineering literature, as shown in Fig. 33 (Chapter 4) the term "hydraulic grade line" is used to designate a curve representing the heights to which water would

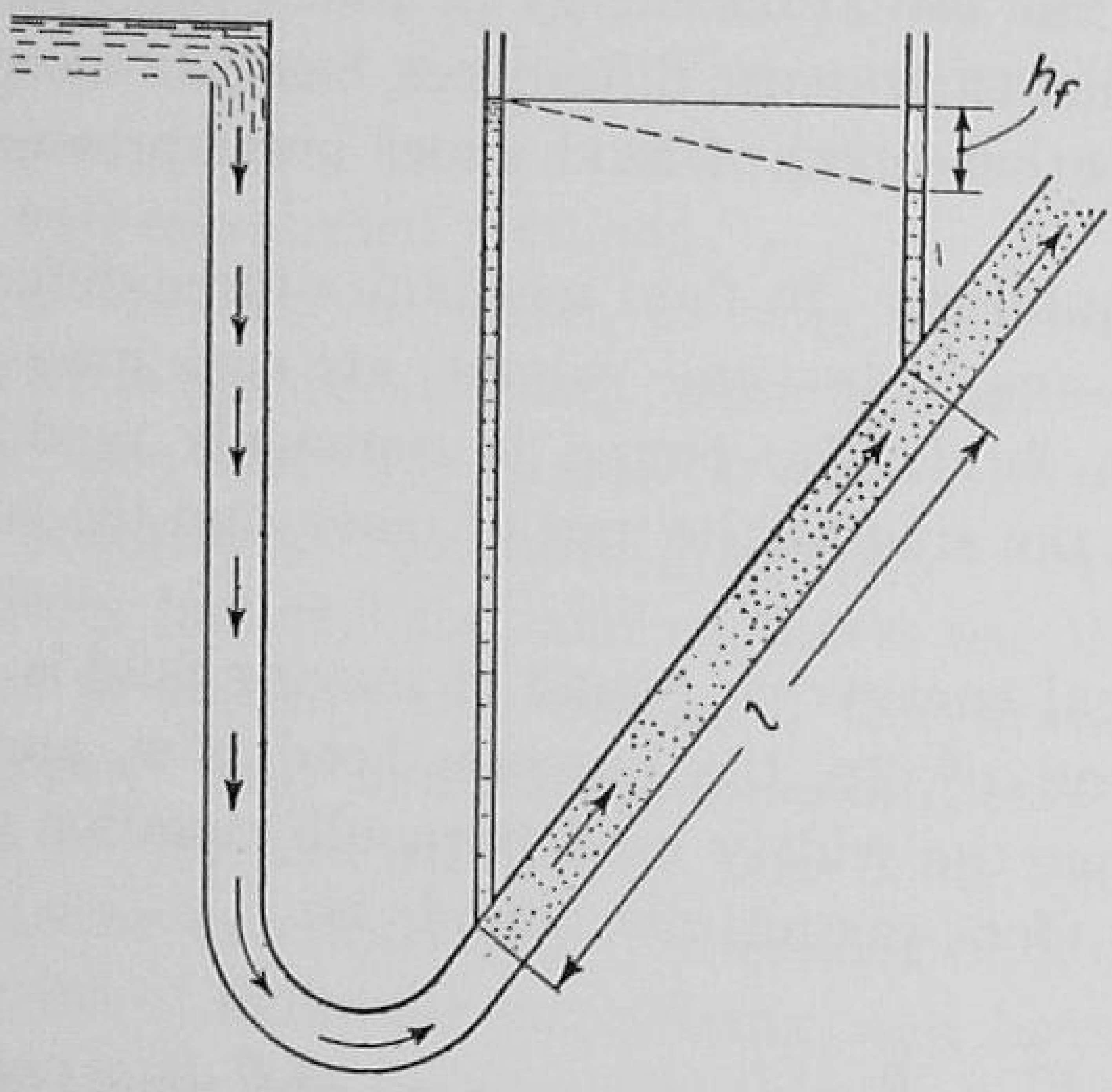


FIG. 125. Illustrating the measurement of the hydraulic slope, h_f/l.

rise in a series of vertical tubes connected to a pipe line through which water is flowing under pressure. For pipes in which the intensity of water pressure is low, the hydraulic grade line will be relatively near the pipe; and for pipes in which it is high the grade line will be farther above the pipe line. The mean velocity of the water flowing in the pipe is independent of the elevation of the hydraulic grade line, but it is dependent on its slope.

Measurement of the hydraulic slope causing linear flow of water in a saturated soil is illustrated in Fig. 125. In a pipe, or a column of soil through which water is flowing, it is the loss of head h_f divided by the length between the points of measurement l, i.e., h_f/l.

The difference in hydraulic head or loss of head between two points in a pipe conveying water under pressure is represented by the difference in elevation of two points on the hydraulic grade line. This

difference in hydraulic head h_f divided by the length l along the pipe between the points at which the hydraulic heads are measured gives the slope of the hydraulic grade line, or better, the hydraulic slope.*

156. Regions of Equal Hydraulic Head A space or volume in which hydraulic head at every point is of the same magnitude is known as region of equal hydraulic head.

A body of still water like a pond or a lake as in Fig. 126, undisturbed by wind and having neither inflow nor outflow, constitutes such

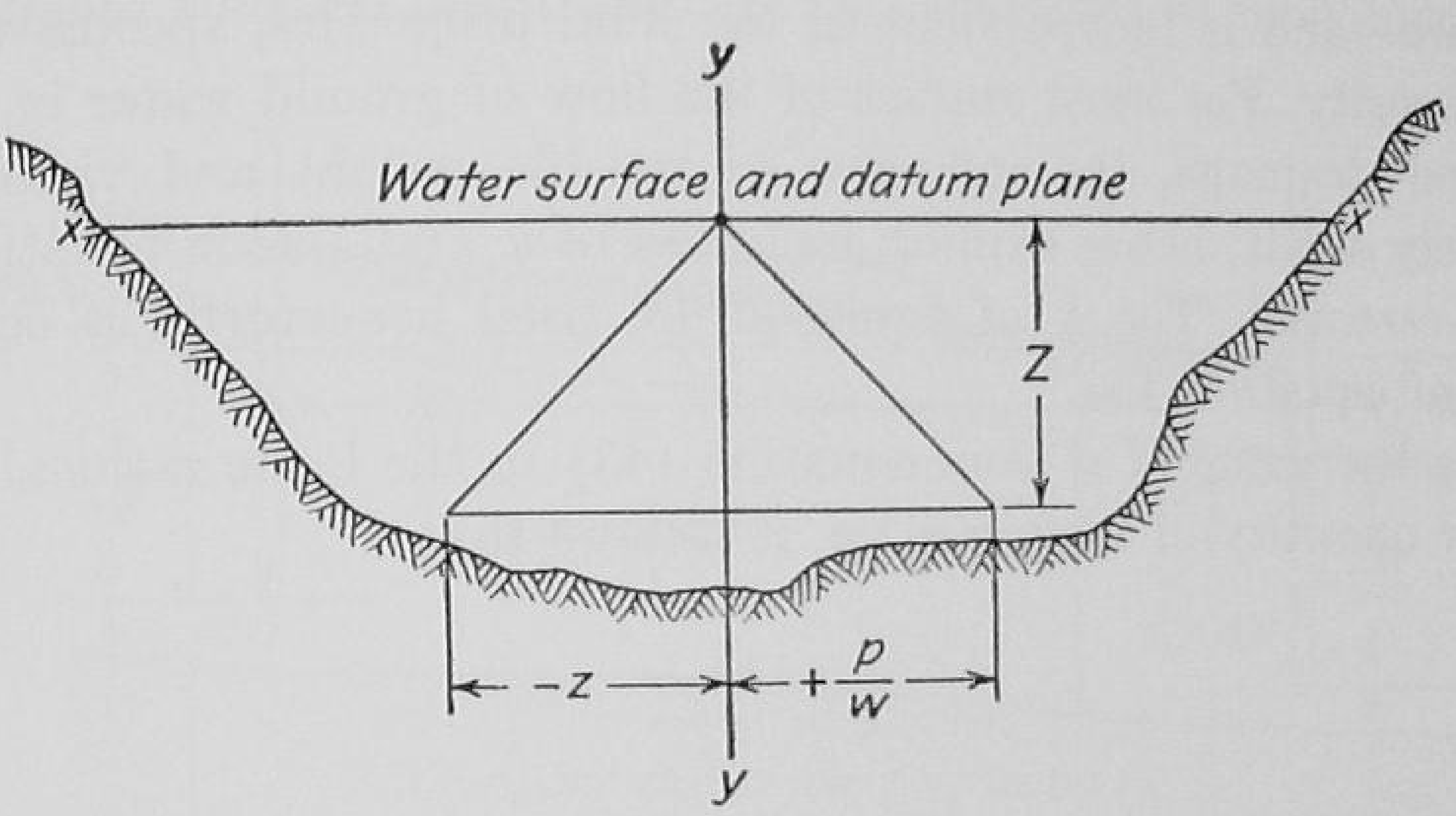


FIG. 126. Illustrating a region of equal hydraulic head in a body of water such as a pond or a lake. The elevation head decreases with increase in depth of water at the same rate that the pressure head increases, thus making the sum of the two a constant.

a region. The surface of the water here taken as datum or reference plane has zero elevation, the same everywhere because the surface is level. Passing from the level water surface downward toward the bottom of the pond or lake, the pressure head p/w increases at the same rate as the elevation head z decreases, hence the hydraulic head $(p/w + z)$ is constant, and the region is one of equal hydraulic head. There are no resultant forces due to change of the sum of elevation and pressure heads in this region. The hydraulic slope is zero.

157. Water Flow in Saturated Soils The velocity v for steady streamline flow in saturated soils is proportional to the soil permeability k and the hydraulic slope in the direction of flow as shown by the widely used Darcy equation

$$v = k\frac{h_f}{l} \tag{43}$$

* The term "hydraulic gradient" is used by some writers to designate the "slope of the hydraulic grade line."

The Darcy equation may include the specific weight of the fluid w and the dynamic viscosity μ and have the form

$$v = \left(\frac{k'w}{\mu}\right)\frac{h_f}{l} \tag{43a}$$

The permeability k' has the physical dimensions of area or L^2. When defined, as in equation 43a, the permeability is influenced only by the size and shape of the soil particles and pores—the soil texture and structure—and is independent of the fluid properties, specific weight, and viscosity. For most studies of the flow of ground water in irrigation and drainage, the influence of specific weight and viscosity is relatively small; hence explicit inclusion of w and μ as in equation 43a is not essential. The k of equation 43, used henceforth, is equal to $k'w/\mu$ of equation 43a.*

Using the value of v from equation (43) in the basic rational equation for quantity of flow, $q = va$, it follows that

$$q = \frac{kh_fa}{l} \tag{44}$$

in which a is the gross area at right angles to the flow direction.

In saturated soils water is under compression. The pressure intensity at any point is

$$p = wh$$

and the pressure head

$$h = p/w$$

Let the hydraulic head at point 1 be h_1 and at point 2 be h_2. Then:

$$h_1 = \frac{p_1}{w} + z_1$$

$$h_2 = \frac{p_2}{w} + z_2$$

Assume that h_1 is greater than h_2 and that the two points are a distance l apart; then

$$h_f = h_1 - h_2 = \left(\frac{p_1}{w} + z_1\right) - \left(\frac{p_2}{w} + z_2\right)$$

* $k = \frac{L}{T} = L^2 \times \frac{F}{L^3} \times \frac{L^2}{FT} = \frac{L}{T}$.

and hence, the hydraulic slope

$$\frac{h_f}{l} = \frac{[(p_1/w) + z_1] - [(p_2/w) + z_2]}{l} \tag{45}$$

In equation 45, w is the specific weight of the water and $\frac{p_1}{w}$ and $\frac{p_2}{w}$ are the pressure heads; z_1 and z_2 are the elevation heads with respect to a selected datum plane.

Applications of the equations 43, 44, and 45 for ground-water flow in saturated soils are illustrated by two examples of field conditions:

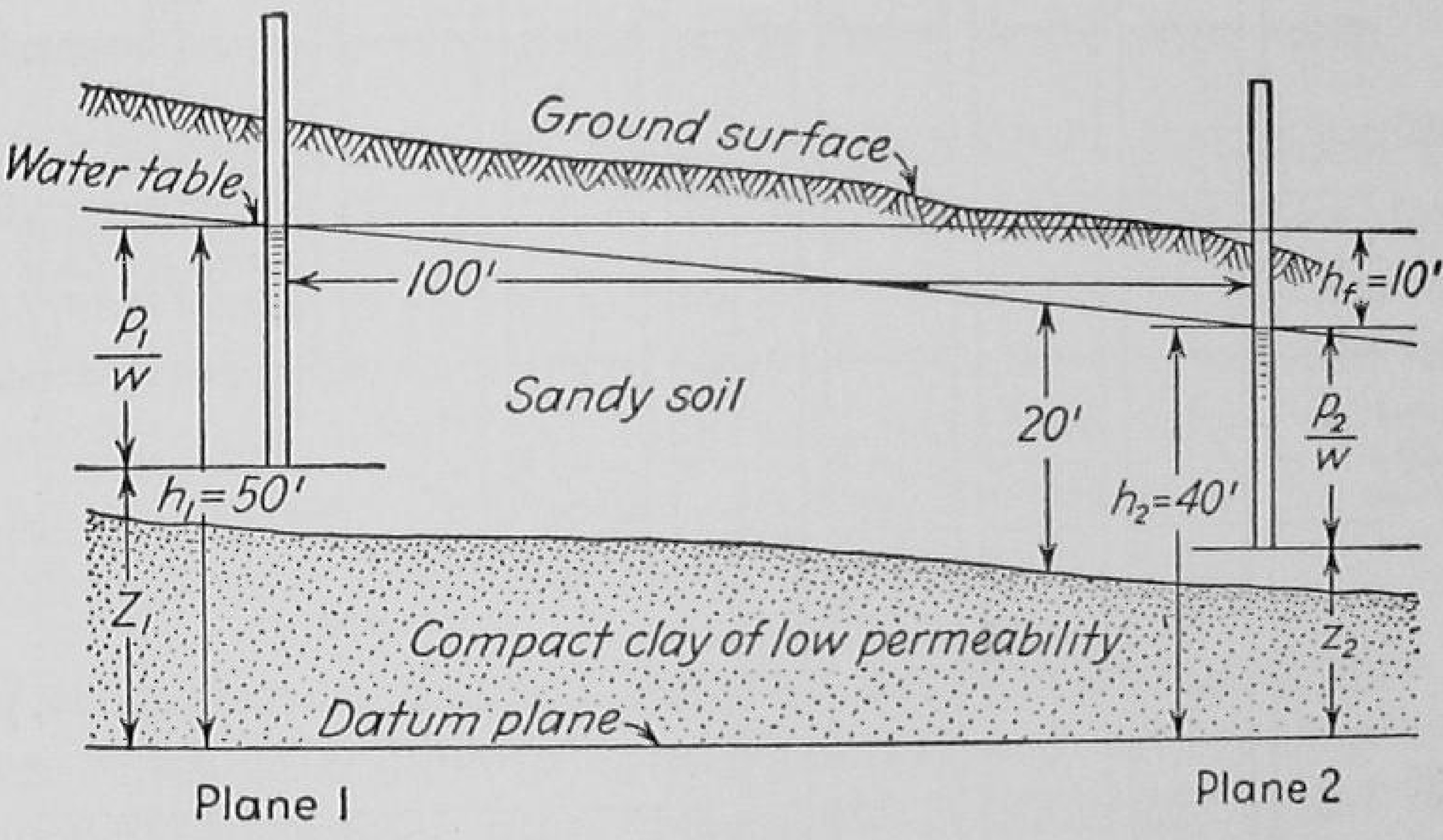


FIG. 127. Flow of unconfined ground water in saturated sand overlying a compact clay.

the first for flow of *unconfined or free ground water* in sand under a small hydraulic slope (Fig. 127), and the second for upward flow of water through a 40-ft stratum of clay over an artesian aquifer of gravel in which the water is under pressure, or *confined* (Fig. 128). Figure 127 illustrates unconfined ground water flowing through sandy soil overlying a compact clay. The piezometer at plane 1 shows a hydraulic head $h_1 = (p_1/w) + z = 50$ ft, and at plane 2, $h_2 = 40$ ft. Therefore, as the flow distance is 100 ft, the hydraulic slope, by equation 43, is 10/100 and the velocity is $\frac{1}{10}\,k$. Selecting an average k of 1200 ft per year, or 3.8×10^{-5} ft per sec, the approximate velocity of flow through the sand is $v = 120$ ft per yr, and the quantity of flow in a section 1000 ft long and 20 ft deep, by equation 44, is

$$q = \frac{3.8 \times 1000 \times 20 \times 1}{100{,}000 \times 10} = \frac{76}{1000} \text{ cfs} = 34.2 \text{ gpm}$$

For the second example, the results of piezometer measurements at

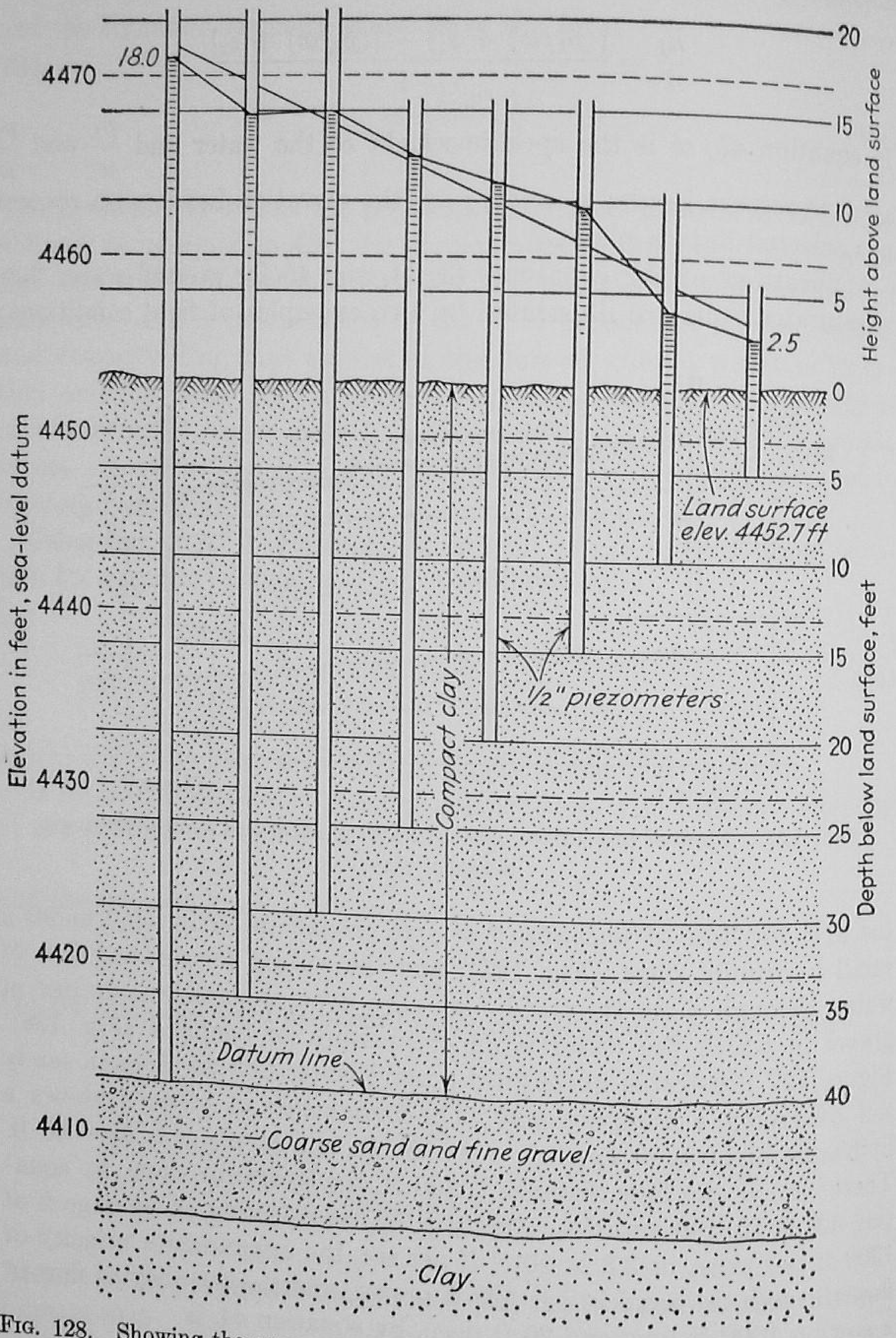


FIG. 128. Showing the average pressure head, p/w, based on 24 measurements at eight elevations in a clay stratum overlying an artesian aquifer. (*Utah Agr. Exp. Sta. Bul.* 259.)

eight different elevations in a clay soil overlying an artesian gravel aquifer are presented in Fig. 128. The level surface at the top of the gravel is taken as the reference plane, or the plane of zero elevation head. The permeability of the clay soil has been measured and found to average 5 ft per yr. Then, to find the average velocity of the flow from the 40-ft soil depth up to the 5-ft depth, in feet per year, using equations 43 and 45,

$$v = \frac{5\,[(58.0 + 0.0) - (7.5 + 35.0)]^*}{35}$$

$$= \frac{5 \times 15.5}{35} = \frac{77.5}{35.0} = 2.20 \text{ ft per yr}$$

If the hydraulic slope and the soil permeability, as measured at the place represented by the data of Fig. 128, were the same for one section, or 640 acres of land, then the annual loss of water from the artesian aquifer, due to upward flow through the clay soil and surface consumptive use, would be 1408 acre-feet. The values of pressure head and elevation head above recorded are presented to show the application of the Bernoulli energy equation.

158. Piezometers to Measure Pressure Heads in Saturated Soils The pressure heads p/w illustrated in Figs. 127 and 128 are measured by driving small-diameter pipe, designated piezometers, to the desired depth. A much-used driving hammer and driving head for either ¼-in. or ⅜-in. pipe is shown in Fig. 129.

When the piezometers are driven, a plug of soil from 6 to 12 in. in length forms in the lower end of the pipe. This plug is removed by flushing (Fig. 130), which consists of pumping water down to the bottom of the piezometer through plastic tubing. This water flows up through the annular space between the tubing and wall of the pipe and carries with it soil in suspension. Flushing is continued until a small cavity has been formed below the end of the pipe and the water becomes clear. The plastic tubing is marked for the length of the piezometer, and care is taken not to push the tubing more than 3 or 4 in. below the end of the piezometer.

In soils of average permeability the water in the piezometer reaches an equilibrium level in a few minutes, but in soils of low permeability several hours may be required for the water to reach an equilibrium level.

* In practice, to get the loss in hydraulic head it is essential only to measure the difference in elevation of the water in the two piezometers, that is (18.0 − 2.5) = 15.5 ft.

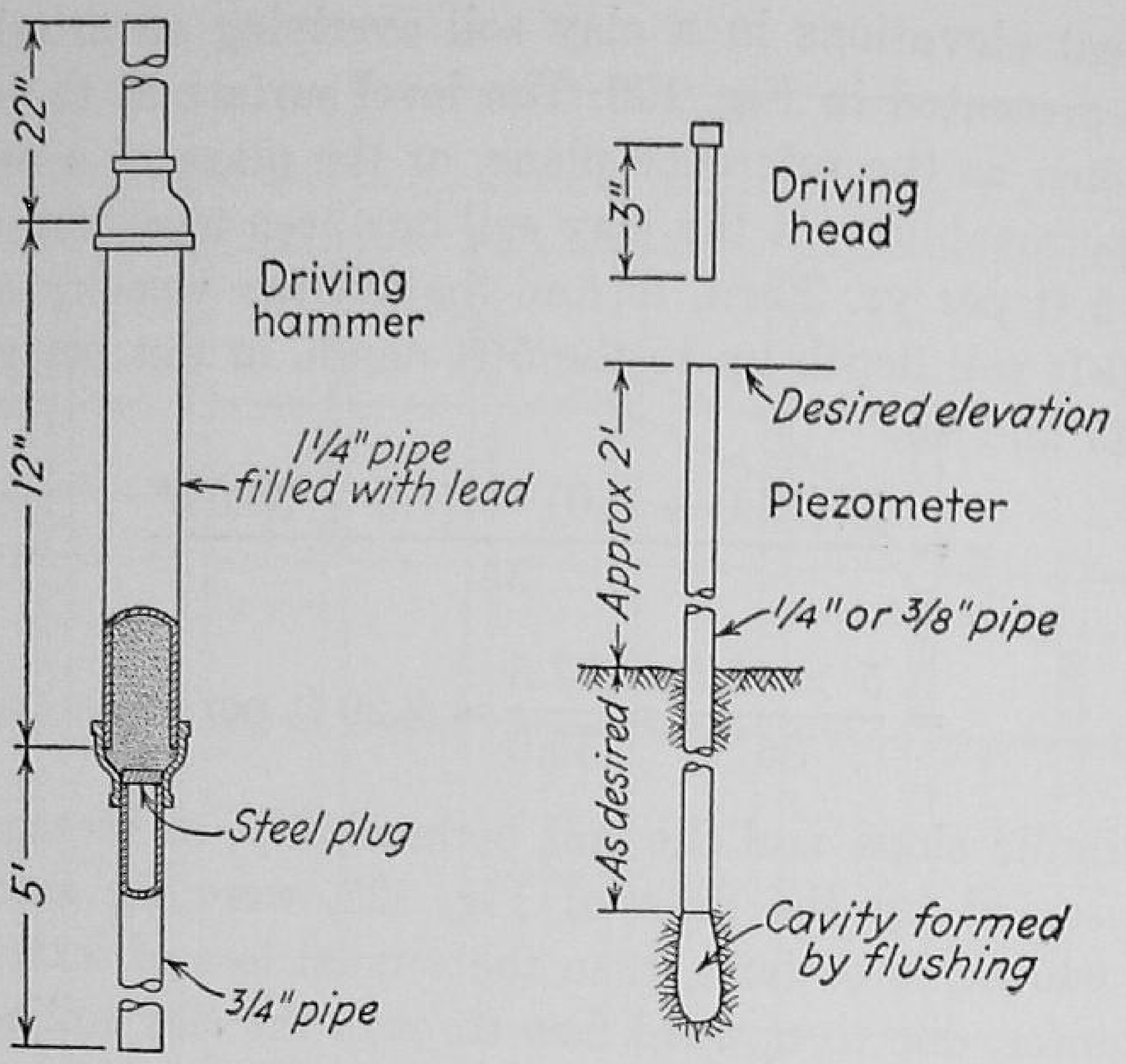


FIG. 129. Detail of driving hammer and piezometer. (*Agr. Eng.*, Vol. 24, No. 10.)

FIG. 130. Flushing the piezometer. (Courtesy U.S. Regional Salinity Lab.)

In highly compacted soils, and in those containing fine gravel that cannot pass upward through the annular space during the flushing operation, a rivet is inserted in the end of the piezometer before it is driven. The pipe is then driven to a point about 3 in. below the desired level and pulled up 3 in. so that the rivet can easily be punched out with a rod before flushing. This eliminates difficulty

FIG. 131. Reading the piezometer with an electrical sounder gage. (Courtesy U.S. Regional Salinity Lab.)

sometimes encountered in removing the soil plug formed in the end of pipe. In most soils, however, this plug can be removed by flushing in less time than is required to punch out the rivet.

Reading the piezometer with an electric sounder is shown in Fig. 131. For measuring the elevation head, an engineer's level is used.

159. Soil-Permeability Measurements The permeability of saturated soils varies greatly. In irrigation and drainage studies, as related to soils, permeability is the dominant variable, some soils being as much as 100,000 times as permeable as others.

Knowledge of soil permeabilities is essential to progress in studies of water-conveyance efficiencies, water-application efficiencies, and in

the design of drainage systems, for the reclamation of saline and alkali soils.

Permeabilities are influenced by the size and shape of pore spaces through which water flows; and by the specific weight and viscosity of the soil water, as shown in equation 43a; its temperature, and other factors. It is impractical to measure all the factors that influence permeability, but it is practical and very essential to measure the permeability of soils in the laboratory and in the field.

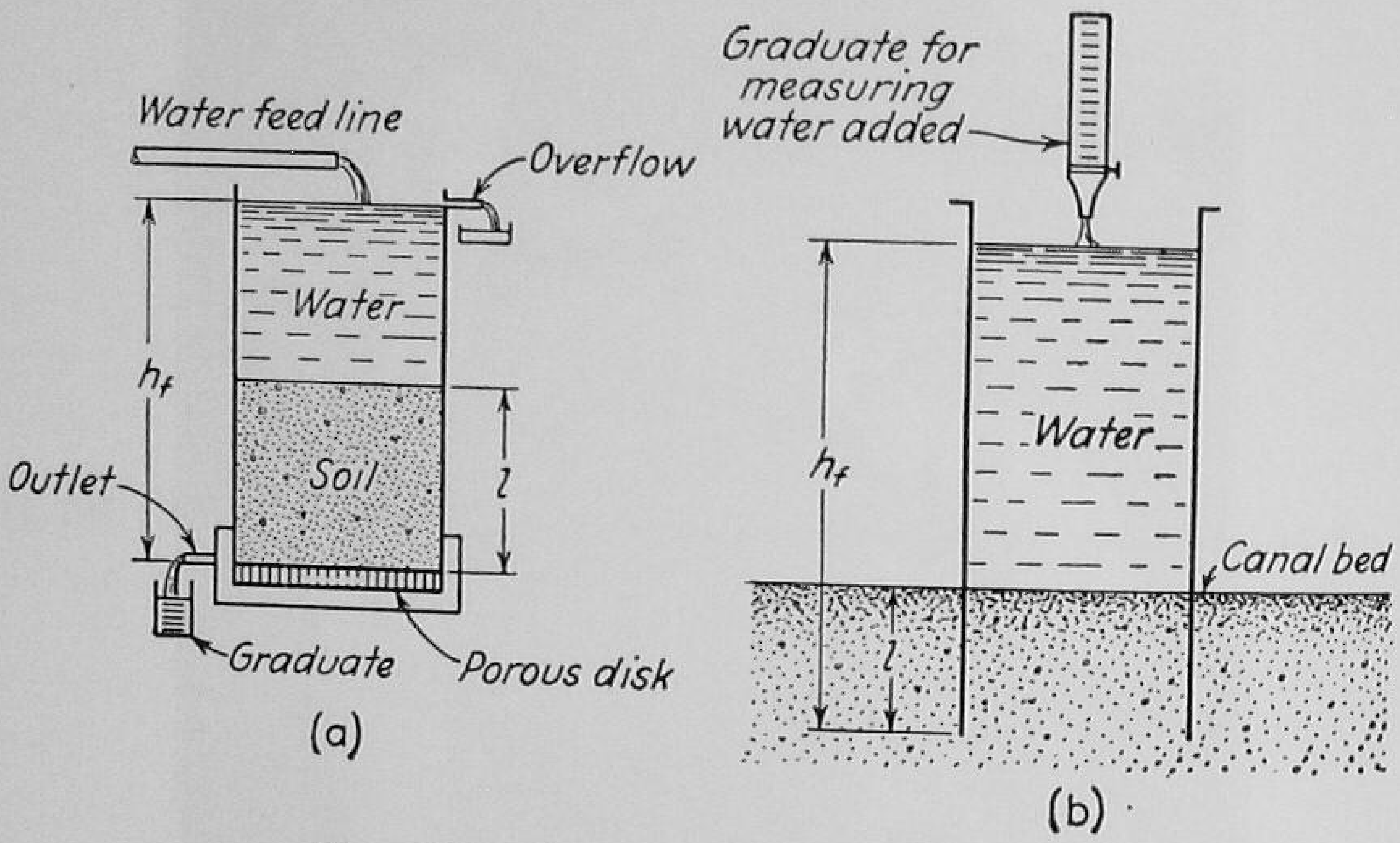


FIG. 132. Constant-head permeameters.

Two of the many types of equipment for measuring the permeability of soils are the constant-head permeameter and the variable-head permeameter. Both these permeameters may be used for laboratory and field measurements. Brief descriptions of each, together with illustrative figures and examples of computations of the permeability k, are included. Results of some field-permeability measurements are presented.

160. Constant-Head Permeameter With a constant head maintained by either continuous inflow or frequent additions of water, an approximately steady flow through the soil is obtained. Figure 132 illustrates two constant-head permeameters, one for laboratory tests and one for field studies. Darcy's law for the flow of water in soils is applied for computing the permeability after measuring the volume of flow in unit time q, the gross soil cross-section area at right angles to flow a, the loss of hydraulic head h_f, and the flow length l.

In field studies and undisturbed soil the loss in head and the flow length sometimes cannot be measured accurately at reasonable cost.

If the surface soil consists of a thin layer of low-permeability soil overlying a layer of highly permeable soil, then the loss of hydraulic head and the flow length may be considered respectively as the distance from water surface to the highly permeable soil, h_f, and as equal to the thickness of the top layer of soil, l, as indicated in Fig. 132. Using symbols defined above and solving the Darcy flow equation 44, for the permeability it follows that

$$k = \frac{ql}{h_f a} \tag{46}$$

For example, where the permeameter having an area of 1.19 sq ft was used, the flow of water was 0.336 cu ft in 0.4 hr, the loss in hydraulic head flowing through 1 ft of soil was 2.4 ft, and therefore the permeability is

$$k = \frac{0.336 \times 1 \times 12}{0.40 \times 2.4 \times 1.19} = 3.5 \text{ in. per hr, or } 2600 \text{ ft per yr}$$

Irrigation engineers utilize one or more of several different units of volume, area, and time with the term permeability. The units cubic feet per square foot per day, or acre-inches per acre per hour (or simply surface feet per day and inches per hour), are typical. When water flows in saturated soils vertically downward under the force of gravity only the hydraulic slope is considered as unity.

Table 30 includes permeabilities from 0.005 to 25 in. per hr (column 2) and from 1/100 to 50 cu ft per sq ft of soil in 24 hr (column 1), the relative variation being from 1 to 5000.

One cubic foot per second is equal approximately to 1 acre-inch per hour. On this basis, column 2 of Table 30 gives the number of cubic feet per second that would be required to maintain a stream of water percolating vertically downward through 1 acre of soil having different permeabilities. For example, line 24 shows that a stream of 1 cfs per acre would equal 2 cu ft per sq ft per 24 hr.

The computed data of Table 30 will enable the student to interpret more easily the permeability field tests reported in Table 31. These measurements were made on field soils by two methods. Eighteen-inch-diameter iron cylinders 20 in. long and open at both ends were driven into the soil in its natural condition. Measured amounts of water were added to the soil frequently enough to keep it well covered and under constant head.

Similar measurements were made in the field plat method, the essential difference being a larger area of soil being submerged. The plats used ranged from 32 to 1254 sq ft in area. As noted in Table 31,

TABLE 30

COMPARISON OF PERMEABILITY OF SOIL TO WATER AS STATED IN DIFFERENT UNITS, WITH THE WATER CONDUCTIVITY

Line No.	1	2	3	4
	Permeability in			Water Conductivity k
	Cu Ft per Sq Ft per 24 Hr	Surface Inches per Hour	Cfs per Acre	
1	0.01	0.005	0.005	3.59×10^{-9}
2	.02	.010	.010	7.18×10^{-9}
3	.03	.015	.015	1.08×10^{-8}
4	.04	.020	.020	1.44×10^{-8}
5	.05	.025	.025	1.80×10^{-8}
6	.06	.030	.030	2.16×10^{-8}
7	.07	.035	.035	2.52×10^{-8}
8	.08	.040	.040	2.87×10^{-8}
9	.09	.045	.045	3.23×10^{-8}
10	.1	.05	.05	3.59×10^{-8}
11	.2	.10	.10	7.18×10^{-8}
12	.3	.15	.15	1.08×10^{-7}
13	.4	.20	.20	1.43×10^{-7}
14	.5	.25	.25	1.80×10^{-7}
15	.6	.30	.30	2.16×10^{-7}
16	.7	.35	.35	2.52×10^{-7}
17	.8	.40	.40	2.87×10^{-7}
18	.9	.45	.45	3.23×10^{-7}
19	1.0	.50	.50	3.59×10^{-7}
20	1.2	.60	.60	4.32×10^{-7}
21	1.4	.70	.70	5.02×10^{-7}
22	1.6	.80	.80	5.75×10^{-7}
23	1.8	.90	.90	6.46×10^{-7}
24	2.0	1.00	1.00	7.18×10^{-7}
25	2.2	1.10	1.10	7.90×10^{-7}
26	2.4	1.20	1.20	8.62×10^{-7}
27	2.6	1.30	1.30	9.34×10^{-7}
28	2.8	1.40	1.40	1.01×10^{-6}
29	3.0	1.50	1.50	1.08×10^{-6}
30	3.2	1.60	1.60	1.15×10^{-6}
31	3.4	1.70	1.70	1.22×10^{-6}
32	3.6	1.80	1.80	1.29×10^{-6}
33	3.8	1.90	1.90	1.37×10^{-6}
34	4.0	2.00	2.00	1.44×10^{-6}
35	4.5	2.25	2.25	1.62×10^{-6}
36	5.0	2.50	2.50	1.80×10^{-6}
37	6.0	3.00	3.00	2.16×10^{-6}
38	7.0	3.50	3.50	2.52×10^{-6}
39	8.0	4.00	4.00	2.87×10^{-6}
40	9.0	4.50	4.50	3.23×10^{-6}
41	10	5.00	5.00	3.59×10^{-6}
42	15	7.50	7.50	5.38×10^{-6}
43	20	10.00	10.00	7.18×10^{-6}
44	25	12.5	12.5	8.98×10^{-6}
45	30	15.0	15.0	1.08×10^{-5}
46	35	17.5	17.5	1.26×10^{-5}
47	40	20.0	20.0	1.44×10^{-5}
48	45	22.5	22.5	1.62×10^{-5}
49	50	25.0	25.0	1.80×10^{-5}

the permeability of the sandy loam decreased by approximately one-half in a period of 4 hr, after which it remained constant. The lava-loam permeabilities represent a steady flow. The deep loam measurements at Logan on plat *A* represent only the rapid flow shortly after wetting. On plats *B* and *C* the higher permeabilities represent flow

TABLE 31

PERMEABILITY AND WATER CONDUCTIVITY FIELD TESTS OF DIFFERENT SATURATED SOILS

Class of Soil	Location of Field	Time	Cu Ft per Sq Ft per 24 Hr	Surface Inches per Hour	Cfs per Acre	Water Conductivity *k*	Method
1	2	3		4	5	6	7
Highland Sterling Sandy Loam	Hyrum, Utah	1st Hr.	4.88	2.44	2.44	1.7×10^{-6}	18-in. cylinders used
		2nd	2.92	1.46	1.46	1.0×10^{-6}	
		3rd	3.00	1.50	1.50	1.1×10^{-6}	
		4th	2.50	1.25	1.25	9.0×10^{-7}	
		5th	2.50	1.25	1.25	9.0×10^{-7}	
Medium Depth Lava Loam	Grace, Idaho		1.00	0.50	0.50	3.6×10^{-7}	Plat 25 ft. sq.
	Central Idaho		1.24	.62	.62	4.4×10^{-7}	Plat 18 ft. sq.
			0.68	.34	.34	2.4×10^{-7}	Plat 18 ft. sq.
			.76	.38	.38	2.7×10^{-7}	18-in. cylinders
			.84	.42	.42	3.0×10^{-7}	18-in. cylinders
Deep Loam	Logan, Utah (Greenville)	*Plat* *A* — 1st day	9.0	4.5	4.5	3.2×10^{-6}	Plats 33 ft. by 38 ft.
		B — 1st day	5.68	2.84	2.84	2.0×10^{-6}	
		2nd day	2.24	1.12	1.12	8.0×10^{-7}	
		C — 1st day	4.78	2.39	2.39	1.7×10^{-6}	
		2nd day	1.48	.74	.74	5.3×10^{-7}	
	Richfield, Utah		1.40	.70	.70	5.0×10^{-7}	18-in. cylinders

shortly after wetting, and the lower ones represent a more nearly steady flow 12 hours after wetting. Clay soils transmit water slowly, and field measurements of permeability of clay soils are meager. Most of the measurements for clay soils thus far have been made under laboratory conditions.

161. Variable-Head Permeameter The variable-head permeameter, shown in Fig. 133, is adapted to the measurement of the permeability of fine-textured, compact soils of low permeability. It consists of a

cylinder with a conical top to which is attached a vertical glass tube of small diameter. The cylinder is pressed into the soil to a known depth, and then the whole apparatus is filled with water. As the water percolates through the disk of soil in the cylinder the water in the glass tube drops. Since the cylinder is usually made with an area 100 or more times that of the glass tube, a small volume of water percolation registers as a large drop in the glass tube. The permeability

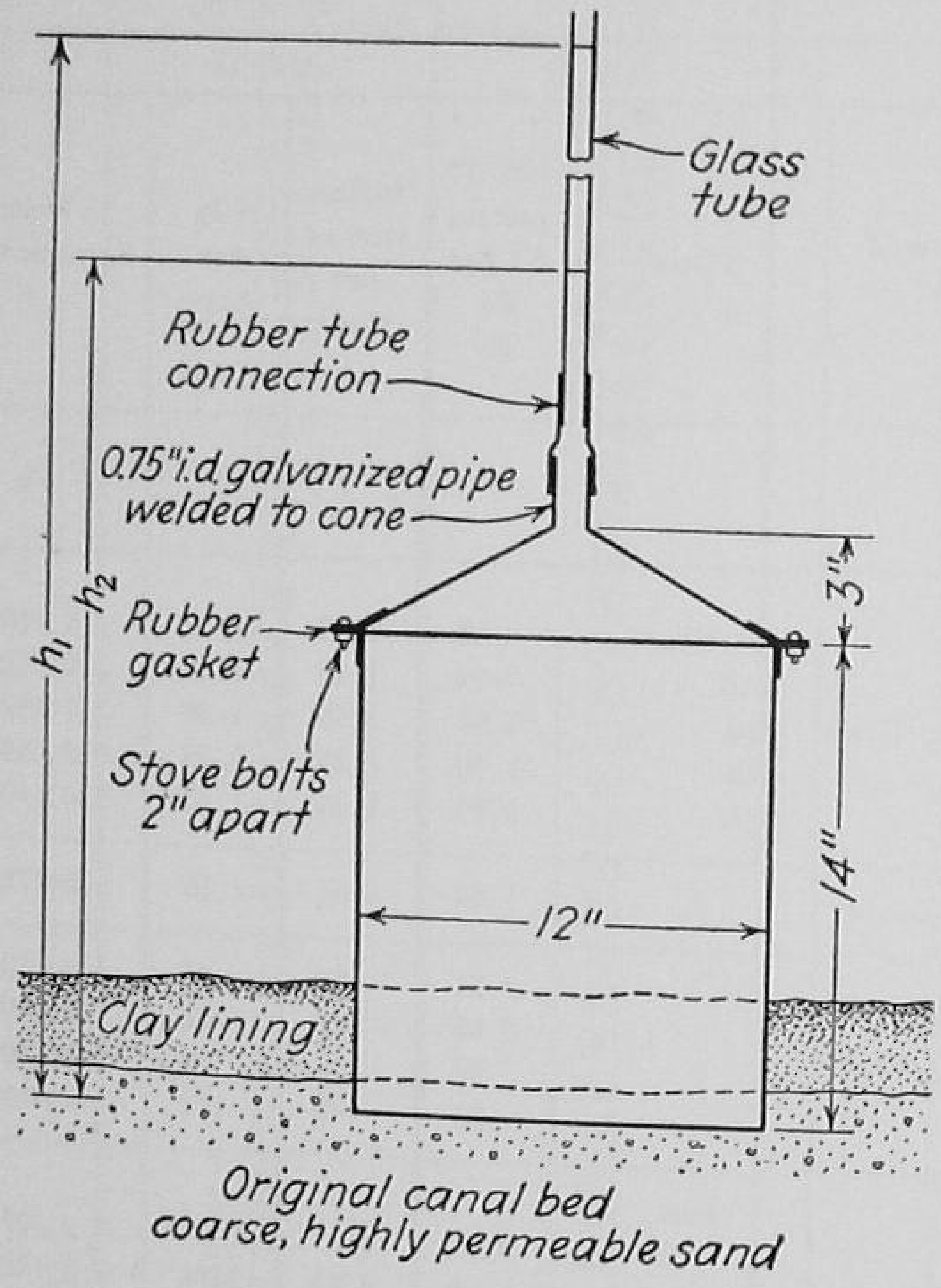


FIG. 133. Variable-head permeameter.

k is computed from the initial and final reading of the water head in the glass tube $(h_1 - h_2)$, the time interval t, the thickness of the soil in the cylinder or flow length l, and the ratio of the area of the glass tube to that of the cylinder a/A. The formula is:

$$k = \frac{2.3al}{At} \log_{10} \frac{h_1}{h_2} \tag{47}$$

For example, for the measurement of the permeability of a clay lining of a canal, the following values were obtained:

$a = 0.26$ sq in.	$t = 6.2$ hr
$A = 153.20$ sq in.	$h_1 = 66.1$ in.
$l = 5.16$ in.	$h_2 = 59.1$ in.

Then

$$k = \frac{2.3 \times 0.26 \times 5.16}{153.2 \times 6.2} \times \log_{10} \frac{66.1}{59.0} = 1.6 \times 10^{-4} \text{ in./hr}$$

$$= 0.13 \text{ ft/yr}$$

The principal difficulty encountered in experience with this permeameter in field tests was the tendency of the cylinder to rise because of the pressure exerted on the inside of the cylinder by the column of water in the glass tube. To overcome this tendency a load was placed on top of the cylinder.

The variable-head permeameter measures the permeability of the canal bed or lining but not the seepage rate from the canal when in use. In order to determine the seepage rate it is necessary also to know the hydraulic slope causing flow through the canal bed.

162. Water Flow in Unsaturated Soils In soils that are not saturated, water flows as a liquid and also as water vapor. The velocity of water flow, due to any selected hydraulic slope, is greater for soils near field capacity than for soils having moisture percentages near the wilting point. It is probable that in soils having moisture percentages near the field capacity the velocity of flow for a soil of given moisture content is proportional (approximately) to the hydraulic slope. In other words, Darcy's law for the velocity of flow in saturated soils probably applies also to many unsaturated soils having moisture percentages near the field capacity. In soils that are not saturated the water flow is caused by a pull or a tension force, not a compression force as in ponds, lakes, and saturated soils.

Consider, for example, the upward capillary flow of water from a shallow water table to the soil surface. When the surface soil has a high moisture percentage the moisture tension is low and the velocity of upward flow, if any, also is low, but as the surface soil moisture is decreased by evaporation, or transpiration by growing plants, the tension increases and upward flow increases.

Research workers in soils, irrigation, and drainage are developing facilities, equipment, and methods for measuring the tension head* at

* The term "head" is proposed by the author because of the custom of research workers to report the "tension" in centimeters of mercury or feet of water, both *length units* represented in engineering language by the term "head," and by equation 42f in which each of the three terms is energy per unit weight which is also a length. Surface tension in fluids is a force per unit length F/L. The tension force tending to pull water through a given cross-section area of soil from points of high moisture percentage to those of lower moisture percentage is regarded as force per unit area, or F/L^2.

different points in unsaturated soils of different moisture contents. For horizontal flow the velocity is considered directly proportional to the tension-head slope. One of the devices for measuring tension head is described in the next article.

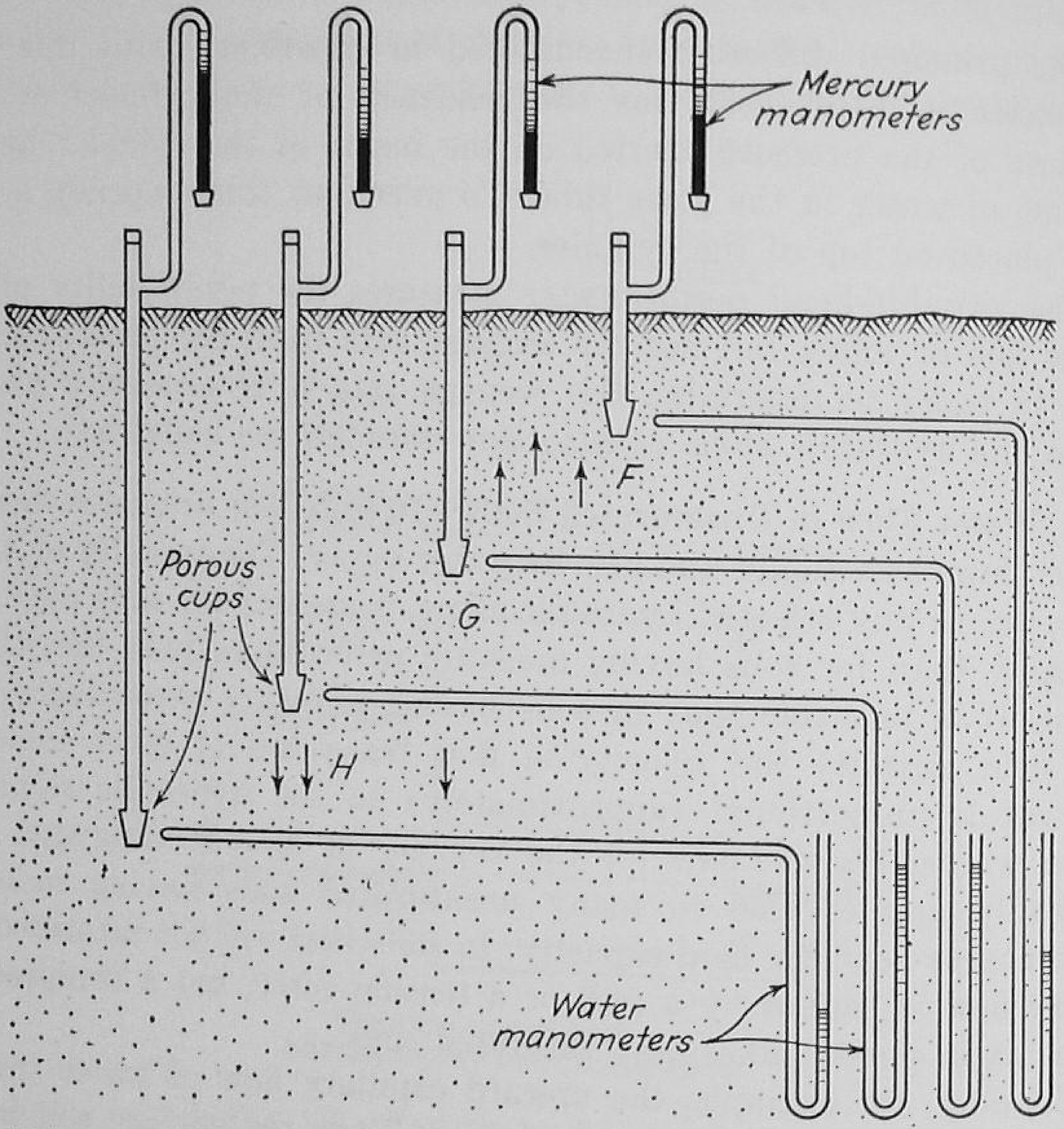


FIG. 134. A typical tensiometer installation employing mercury manometers. The equivalent water manometers are shown at right. (*Agr. Eng.*, Vol. 22, p. 326.)

163. Tensiometers to Measure Tension Heads in Unsaturated Soils The tension force of water in unsaturated soils has been designated by different expressions such as soil pull, the force of suction, and capillary tension. Different names have been suggested to designate the devices designed to measure this attractive force. Gardner and Richards, measuring the energy per unit mass resulting from capillary tension, or the capillary potential, called their instrument a *capillary potentiometer*. In 1935, these authors proposed the name *tensiometer* for the porous-cell vacuum gage instruments for measuring the moisture tension. This name has become common. One type of tensiometer is illustrated in Fig. 134.

It is expedient to use mercury manometers, as shown near the top of Fig. 134, for this type of installation. The manometer readings indicate that moisture is moving upward in soil interval F because of higher hydraulic head in the *upper* porous cup. Also, water is moving

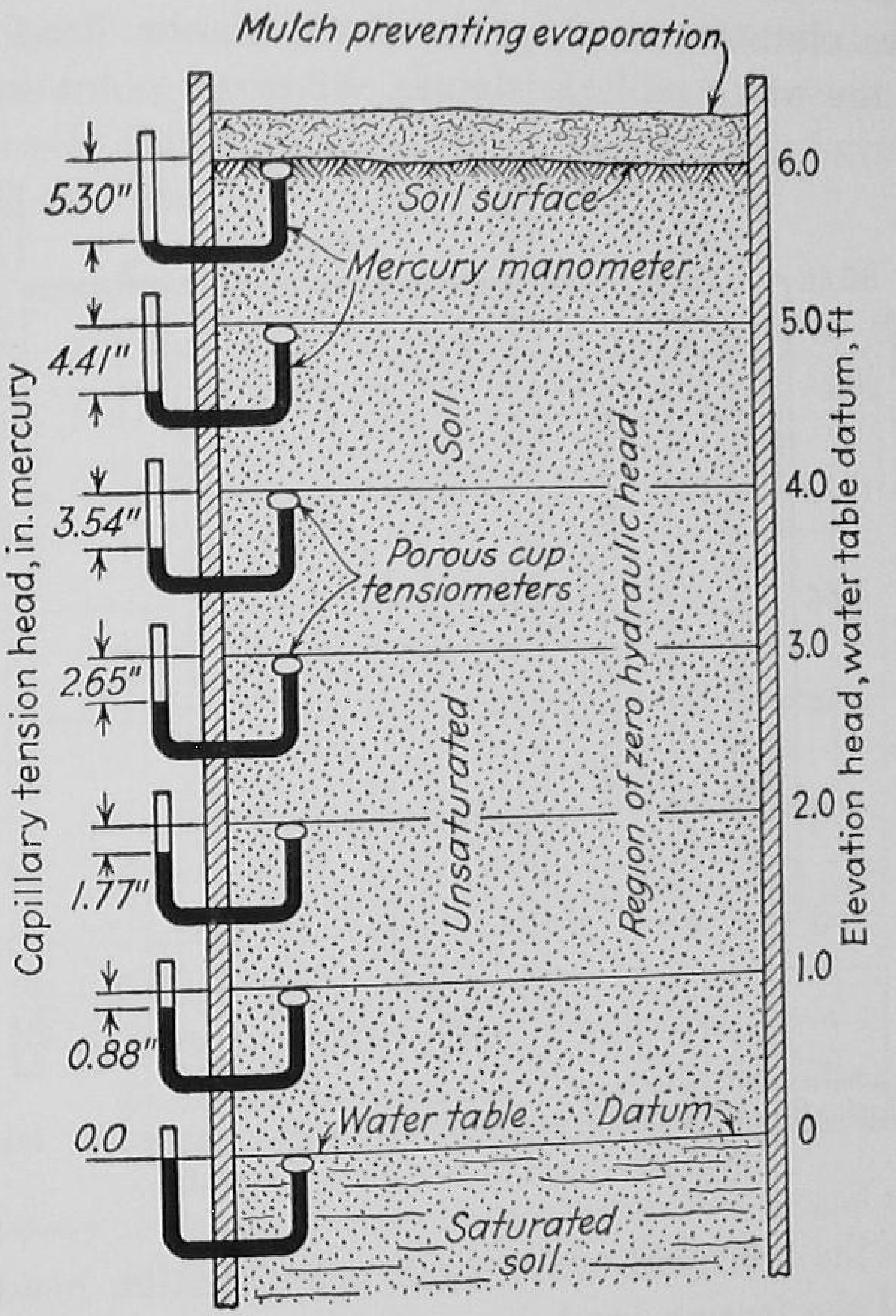


FIG. 135. Illustration of capillary water above the saturated soil and water table, in a region of equal hydraulic head, there being no flow either up or down.

downward in interval H because of gravity and the higher tension head in the *lower* porous cup. In the interval G the hydraulic head $(h_t + z)$ is everywhere the same, the soil moisture is at rest, and the hydraulic slope is zero.

164. Equal Hydraulic Heads in Unsaturated Soils If the hydraulic head is equal at all points in a soil, then there is no water flow in any direction. Figure 135 illustrates a soil region of constant hydraulic head in a vertical plane. The water table is the datum for the elevation head. Porous cup tensiometers in the soil at the water-table datum and at each foot above show that the *tension* head at each level is

of the same magnitude as the elevation head. Since tension is a negative force or a "pull," the sum of the tension head plus the elevation head at each level is zero. Select, for example, the 3-ft level. The tensiometer shows a tension head of 2.65 in. of mercury, which is $2.65 \times 13.6 = 36$ in. or 3 ft of water. This negative tension head, plus the positive elevation head, gives the hydraulic head of zero with respect to the water table as datum. At every point in a horizontal

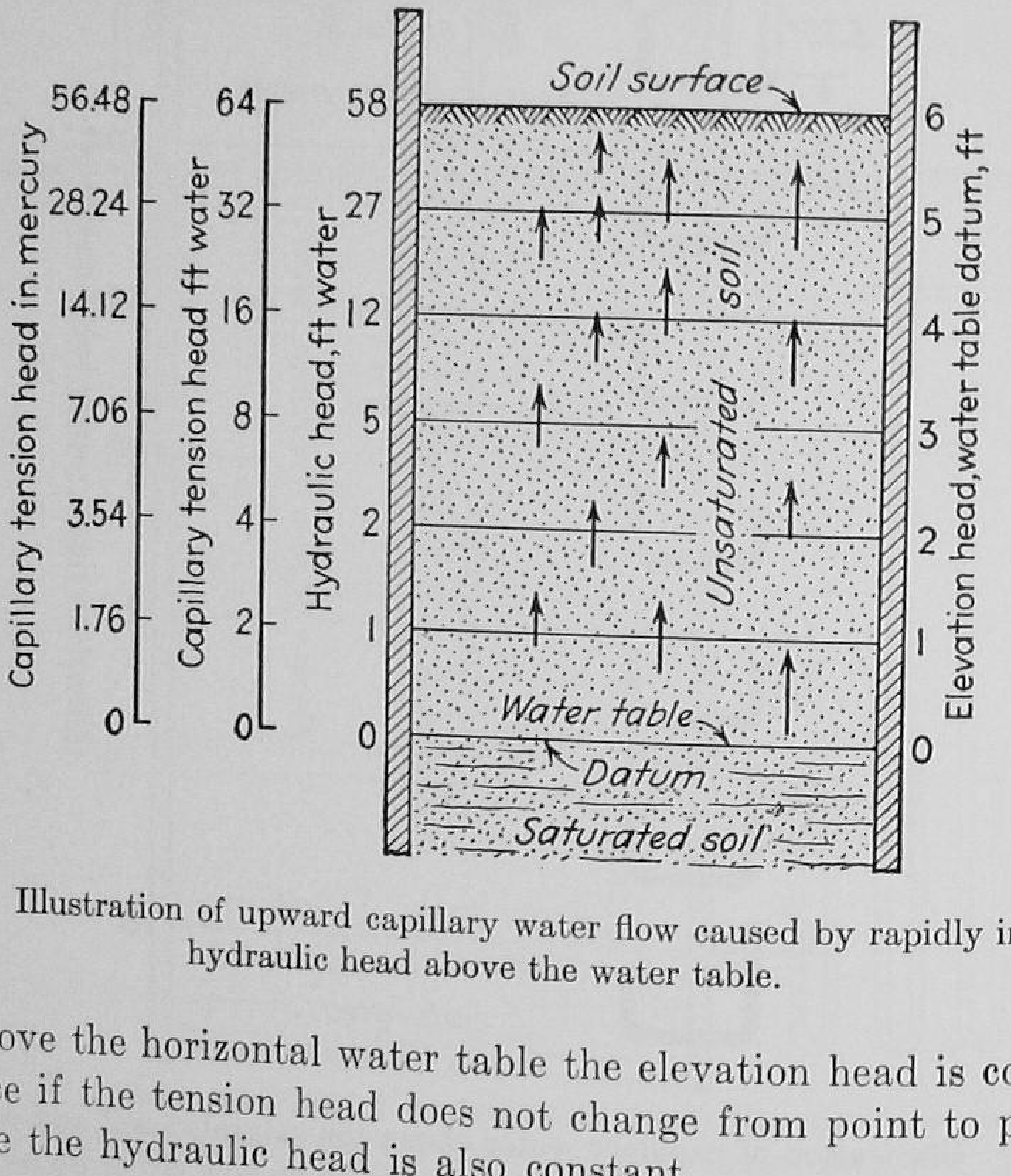


FIG. 136. Illustration of upward capillary water flow caused by rapidly increasing hydraulic head above the water table.

plane above the horizontal water table the elevation head is constant, and hence if the tension head does not change from point to point in the plane the hydraulic head is also constant.

165. Different Hydraulic Heads in Unsaturated Soils Soil above a water table, in which there is a high tension head near the surface, is illustrated in Fig. 136. The tension heads in each foot are assumed. The tension head in a soil at field-moisture capacity may be as high as 12 ft of water. Figure 136 shows that the hydraulic head at each elevation is the algebraic sum of the tension head and the elevation head. It shows also that the hydraulic slope in the 2 ft of soil nearest the water table is $(2 - 0)/2 = 1$, whereas in the surface foot it is $(58 - 27)/1 = 31$ and in the upper 2 ft it is $(58 - 12)/2 = 23$. If the permeability were constant in this soil region, then such large differences in hydraulic slope for steady upward flow would not occur.

Let k_1 equal the average permeability in the 2 ft of soil just above the water table and k_5 equal the average permeability of the upper 2 ft. Then $v_1 = k_1$ because $hf/l = 1$, and $v_5 = 23k_5$. If $v_1 = v_5$, the same quantity flows through each soil depth, and then $k_1 = 23k_5$.

Richards, Neal, and Russell, in 1939, reported many measurements of hydraulic heads and hydraulic slopes in an unsaturated silt loam soil. They measured a hydraulic slope of 23.7 from the 8-in.-soil depth to the 4-in. depth, thus indicating an upward moving force of 23.7 lb on each pound of water.

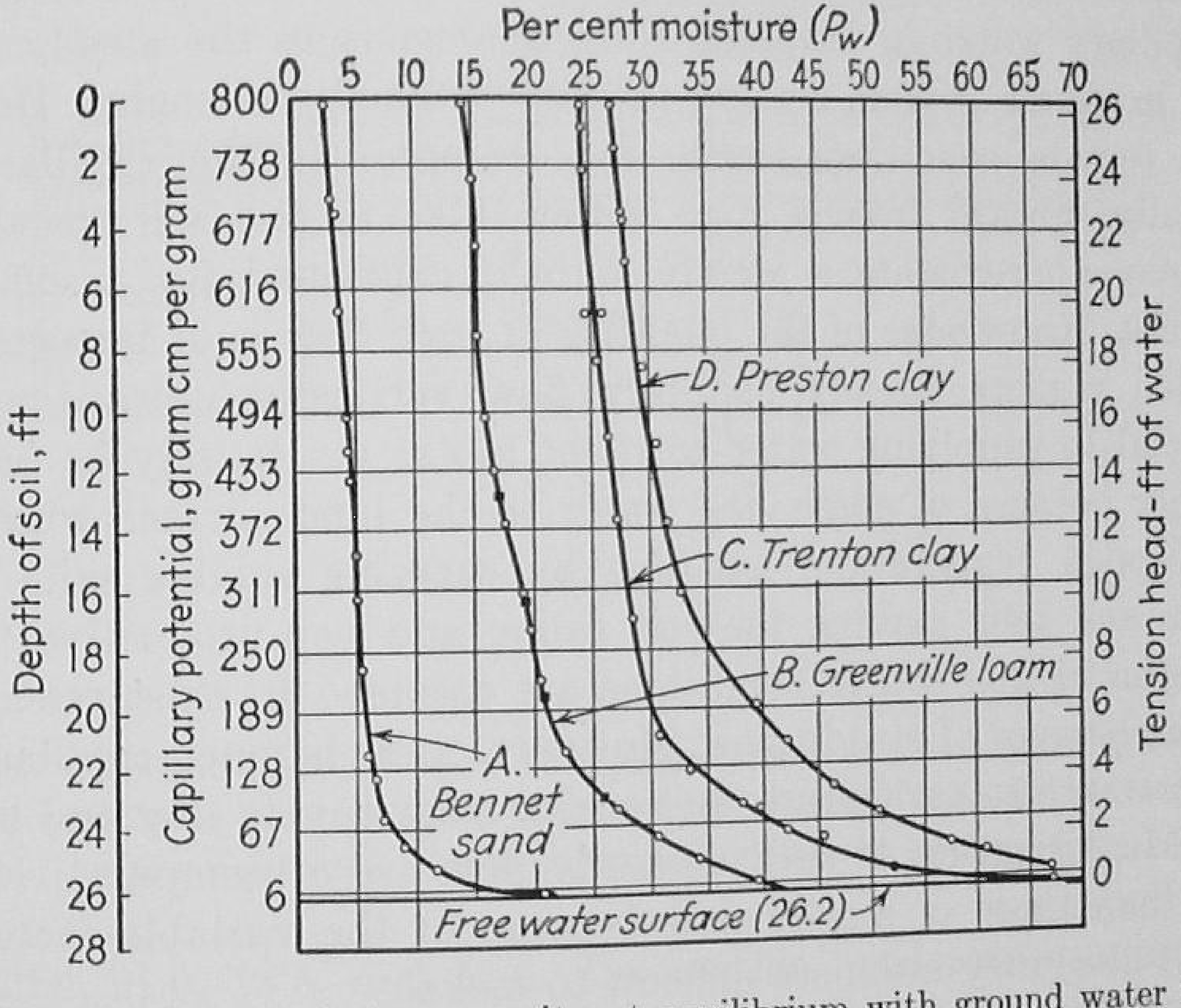


FIG. 137. Capillary moisture capacity at equilibrium with ground water for four types of soil as determined by Richards.

166. Tension Heads and Soil-Moisture Percentages The moisture content of the soil corresponding to a particular tension head is influenced by the soil texture, the soil solution, and the temperature. The first factor influences particularly the curvatures of the capillary water films, and the last two the surface tension of the liquid, and thus all influence the tensions.

It is shown in Chapter 8 that the tension head $h_t = 2T/wr$. The surface tension T and specific weight w can be measured, but it is not feasible to measure the radius r in soils; hence h_t is measured by means of the tensiometer.

Richards found a marked increase in tension head with decrease in moisture content, particularly for fine-textured soils. As shown in Fig. 137, he studied the relation of moisture content at equilibrium to

the tension head in four soils, namely, *A*, Bennett sand; *B*, Greenville loam; *C*, Trenton clay; *D*, Preston clay.*

In the Preston clay, for example, the tension head was only 1 ft at 60 percent moisture, and it increased to 15 ft with 30 percent moisture. For the Greenville loam the tension head was 1 ft for 35 percent moisture and increased to about 25 ft with 15 percent moisture.

167. Steady Capillary Water Flow When the quantity cubic feet per second of water flowing in a canal is constant with time and from point to point along the canal, the flow is designated as steady. A steady flow of capillary water in irrigated soils, analogous to the steady flow of water in canals, seldom occurs; the flow is usually changing. However, under certain conditions, such, for example, as the capillary flow vertically upward from a high water table to the soil surface, the flow may approximate a steady state if continued for a sufficiently long time. Knowledge of the quantity of such flow is of importance in irrigated regions. Steady capillary flow vertically upward may be beneficial in supplying water to plant roots; yet it may be harmful, not only because of conveying water to the land surface where it is lost through evaporation, but also by carrying soluble salts to the surface and thus making the soil saline and non-productive. In the discussion of this article conditions are assumed to exist essential to the maintenance of steady flow. However, there is much capillary flow of importance to agriculture that varies from day to day and hour to hour. Measurements of such unsteady flow are of comparatively less value than those of steady flow because of the variable factors involved; also, they are more difficult to make.

The following example is considered to illustrate the use of the space rate of change in the capillary tension head to determine the steady flow of capillary water through soil in a small horizontal pipe.

168. Steady Horizontal Capillary Flow The flow of capillary water in a soil within a small-diameter horizontal pipe is caused by different capillary tension heads due to soil-moisture differences at the several points in the pipe. The elevation head is constant.

For example, consider the capillary flow within the impervious walls of a pipe of small diameter filled with soil, and having one end con-

* In Fig. 137, the vertical distance above the free water surface represents tension head in feet of water and also capillary potential in gram-centimeters/grams. In the original paper by Richards, published in 1928, and in the first edition of this textbook the tension head was not recorded. Students should make sure that potential in gram-centimeters/grams is *numerically* equal to tension head in centimeters.

nected through a porous plug to a water reservoir as shown in Fig. 138. The elevation of the water surface is kept the same as the axis of the pipe, and consequently there is no positive water pressure in the soil. Water is supplied to the soil from the reservoir on the reader's left by flow through a porous wall. Assume the soil to be a loam of the same temperature, texture, and structure as soil *B* of Fig. 137. The moisture percentages of the soil in the pipe at points distant respectively 0, 2, 4, 6, and 8 ft from the source of water are assumed to be

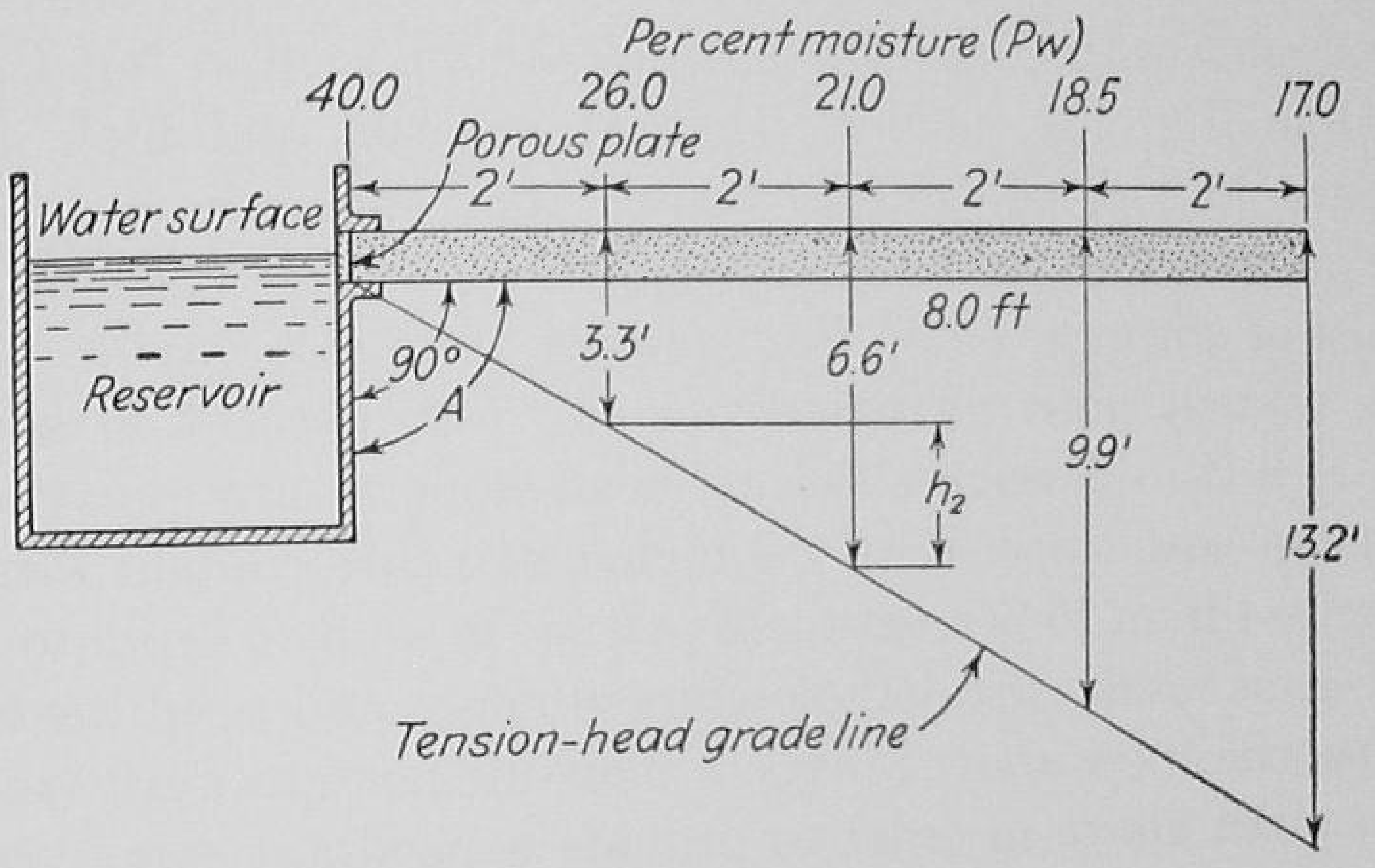


FIG. 138. Illustrating steady flow of capillary water in a horizontal pipe of small diameter containing soil that has a moisture percentage of 40 at the left end and 17 at the right end, and a uniform tension-head slope of 1.65.

40.0, 26.0, 21.0, 18.5, and 17.0. The tension head corresponding to a given moisture content for either of four different soils may be found from Fig. 137. Curve *B* shows that, at the free water surface where the tension head is zero, the moisture percentage is 40; also that, at the point in the soil where the tension heads are 3.3, 6.6, 9.9, and 13.2 ft, the moisture percentages are 26.0, 21.0, 18.5, and 17.0, respectively. The hydraulic slope within the soil column in Fig. 138 is 13.2/8.0 = 1.65. Remembering that there is no change in elevation head along a level pipe, it follows from equation 44 that:

$$q = ka \frac{h_t}{l} = 1.65ka$$

For capillary flow the permeability k is probably less than it is for flow in a saturated soil. For an illustration, the magnitude of k is taken as 1.5×10^{-7} ft per sec. Substituting this value of k it is found that the soil in the horizontal pipe, because of the assumed rate of

change in moisture content, would transmit a quantity of water through 1 sq ft area of

$$q = \frac{1.5 \times 1 \times 1.65}{10^7} \text{ cfs} = 0.64 \text{ cu ft per mo}$$

169. Capillary Flow in Field Soils In homogeneous natural soils in the field, capillary flow is always influenced by gravity. The major practical concern in a study of steady capillary flow is the quantity of flow up or down. The importance of capillary flow vertically downward is sometimes underestimated. The student should keep in mind the fact indicated in Fig. 137, namely, that at medium and high moisture percentages, in soils of uniform texture and structure, a substantial increase in moisture content with depth of soil is essential to the prevention of downward flow. For example, in the Greenville loam, the moisture content must increase from 16 to 20 percent in a vertical distance of 8 ft to develop a tension-head slope at any point equal to the elevation-head slope. With the higher moisture content there must be an increase from 20 percent to 40 percent in an 8-ft depth to accomplish the same result. The soil moisture changes and resulting tension-head slope within the above ranges of moisture content must exceed the examples given above in order to provide a resultant force vertically upward and thus cause capillary water to move upward. That the above statements apply only to comparatively uniform soils, and that the influence of temperature differences and variations in soil solution are neglected, must be kept in mind. Richards has measured the permeability of three unsaturated soils:

A. Light sandy soil.
B. Greenville loam.
C. Preston clay.

In the sandy soil and the clay he found that the magnitude of k increased rapidly as the capillary tension head decreased.

The change in k with change in tension head was relatively small for the Greenville loam. Richards' measurements of k for this loam soil at different tension heads gave results ranging from less than 5.6×10^{-3} to more than 15.4×10^{-3} ft per day.

170. Limitations of Equations Judgment and discretion is essential in the application of the equations of this chapter to the solution of practical irrigation and drainage problems. Because of the many variations from point to point in natural soils, and because of the meager data available on the value of k, it is impractical to attain

precision in computing the flow of water in soils. Moreover, the permeability in a particular saturated soil varies with time. That the flow of water in saturated soils is proportional to the hydraulic slope is well established for small slopes. The urgent need is to evaluate the permeability in many soils and under various conditions, especially in fine-textured soils, which, as a rule, have low permeabilities. Since 1900, engineers have greatly advanced the precision with which the capacities of river channels, canals, pipes, flumes, and other conduits can be estimated by experimentally evaluating the coefficient of roughness n of equation 20, Chapter 4. Progress may likewise be made in the study of the flow of water in soils by centering effort on the evaluation of the permeability, and on a study of its relation to important soil properties, including the moisture content of unsaturated soils. Extended study of the factor k will increase the usefulness and decrease the limitations of the equations presented in this chapter.

11

Saline and Alkali Soils

Excess soluble salts and alkali and drought cause sterility and barrenness of arid-region soils. Although saline and alkali lands are characteristic of arid regions, they are neither of general occurrence nor of uniform distribution. Reclamation of saline and alkali soils, and prevention of excess salts in fertile areas now irrigated, are of paramount importance in arid regions.

In the western part of the United States, the San Joaquin, Sacramento, and Imperial Valleys of California; the Great Basin, including a large part of Utah and Nevada; the Colorado River watershed, comprising parts of Wyoming, Utah, Colorado, Arizona, and California; the Rio Grande River area, including parts of New Mexico and Texas; also parts of the Columbia River Basin and of the Great Plains area east of Rocky Mountains, all contain significant areas of land now nonproductive because of salinity and alkali.

Certain areas in Canada, Mexico, Asia, India, and Australia likewise are sterile because of excess salts and alkali.

Saline soils are soils having excess soluble salts that make the soil solution sufficiently concentrated to injure plants and impair soil productivity. The term, alkali soil, is applied to soils which have an excess of exchangeable sodium either with or without excessive total soluble salts.

These definitions of saline soils and of alkali soils are used and recommended by the United States Regional Salinity Laboratory which was established in 1937 to study the many problems related to excess soluble salts and alkali conditions of soils.

171. Climate and Salinity Arid-region soils contain relatively large amounts of soluble salts. A heavy annual rainfall, such as occurs on the soils of humid regions, causes water to percolate through the soils and carry to the streams, rivers, and oceans large amounts of soluble mineral substances. The scanty rains of arid regions do not penetrate the virgin arid soils deeply enough to cause appreciable percolation.

The greatest depth of penetration of the water from natural precipitation, either the melted winter snow or the wet-season rains, is found to vary from 1 to 4 ft, depending on the depth and time of the precipitation and the nature of the soil. The lack of percolation through arid-region soils, together with excessive evaporation of water in arid regions, gives rise to the accumulation in the soils of soluble salts that are injurious to plant life.

172. Sources and Accumulation of Soluble Salts Mineral soils are derived largely from the weathering of rocks. There is an intimate relation between salt accumulations and the chemical composition of the rocks from which soils are formed. Studies of the geological formations in Utah, Colorado, Arizona, Wyoming, Idaho, and Nevada show that wherever soluble salts are present in very large amounts they originated from materials deposited from concentrated salt waters of some ancient arid-climate sea. The Mancos shale in these states is a typical rock in which large amounts of salts occur. Soils formed directly from these salt-bearing rocks usually contain excessive salts.

Some arid-climate soils that were free from excess salts before cultivation have been rendered non-productive by the use of irrigation water containing excessive quantities. Water that comes from the melted snow and rains on mountain areas of salt-bearing rocks contains appreciable amounts of salts.

Salts continue to accumulate in soils of irrigated areas where greater amounts are brought in than are removed. Irrigation waters contain from $\frac{1}{10}$ ton to 5 tons of salt per acre-foot of water. Some irrigation farmers apply only 2 ft of water per season; others, where the summers are long and hot, apply up to 5 ft of water or more. Where drainage is not provided the irrigation water may add as much as 1 to 10 or more tons of salt each year to an acre of land.

The most effective method for the removal of salt from soil is by means of water which passes through the root zone of the soil, but if the amount carried away is less than brought in by irrigation water, salt will accumulate. To prevent salt accumulation, and consequent decrease in crop yields, irrigators must remove as much salt as is brought in. In some areas an effort is made to spread limited irrigation-water supplies over too many acres, with the result that the soil is not wetted below a depth of a few feet. In other areas, the ground-water table is so close to the surface as to retard or prevent the leaching of the salt from the root-zone soils. In lands having shallow water tables the upward flow of saline ground water results in a continuing accumulation of salt in the surface soil.

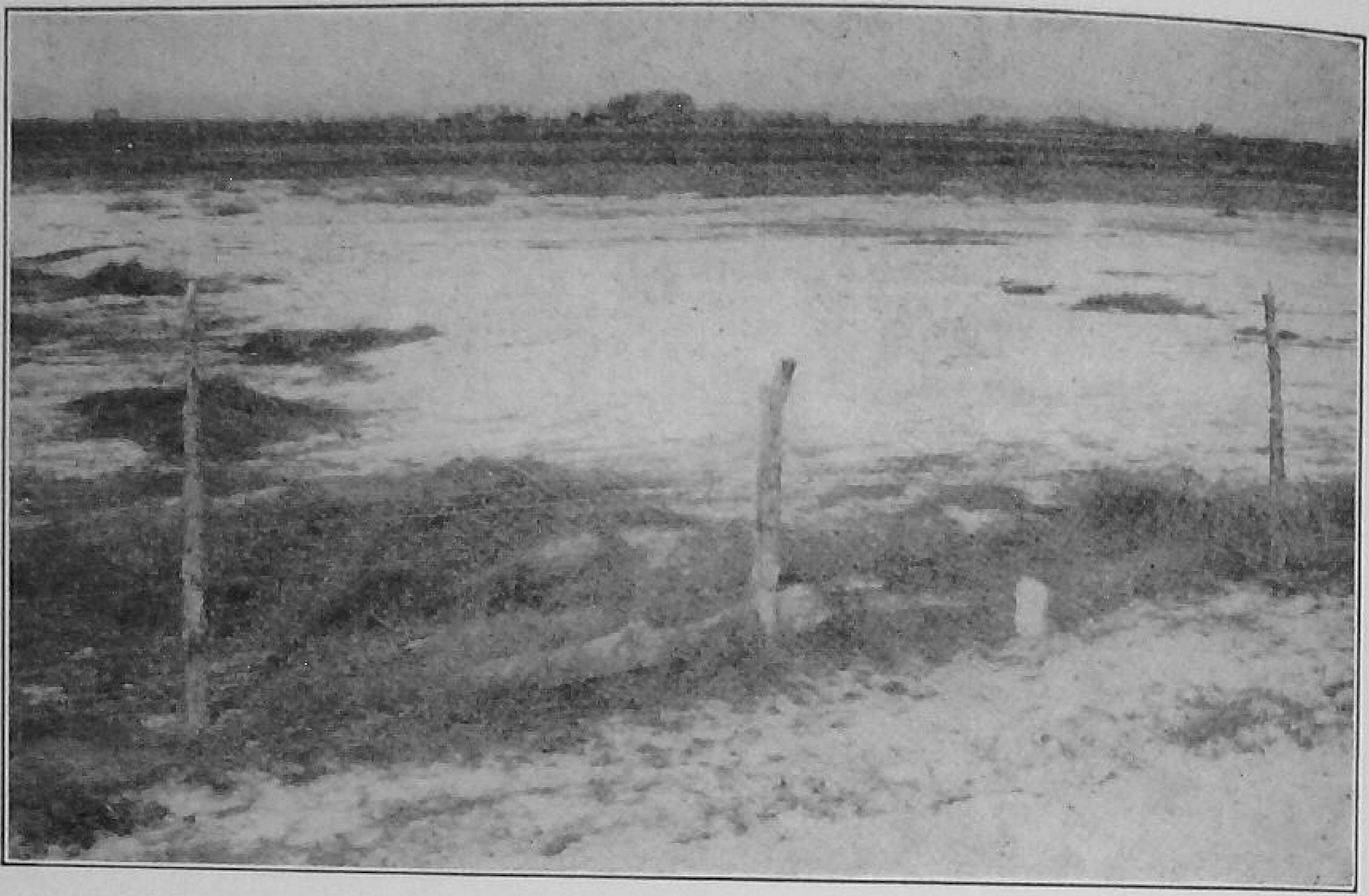


FIG. 139. Surface accumulation of salts on lands near Delta, Utah, prevents the growth of crops without leaching. See also Figs. 142 and 143. (*Utah Agr. Exp. Sta. Bul.* 335.)

FIG. 140. Punjab flax fails to grow on saline spots at Meloland Station, Imperial Valley, California. (*U.S.D.A. Circ.* 707.)

The barrenness that results from excessive accumulation of soluble salts is illustrated in Figs. 139, 140, and 141, showing typical saline lands.

173. Some Basic Terms In a contribution entitled *Diagnosis and Improvement of Saline and Alkali Soils,* the United States Regional Salinity Laboratory presents a glossary of 60 terms together with definitions. The terms that are most used in describing soils having excessive soluble salts and exchangeable sodium are presented here:

Alkali Soil. Soil which has an excessive degree of saturation with exchangeable sodium, either with or without appreciable amounts of soluble salts.

Alkaline. A chemical term referring to "basic" soil reaction where the *p*H is above 7, as distinguished from "acid" reaction where the *p*H is below 7. The *p*H is the logarithm of the reciprocal of the hydrogen-ion concentration. *p*H 7 is neutral.

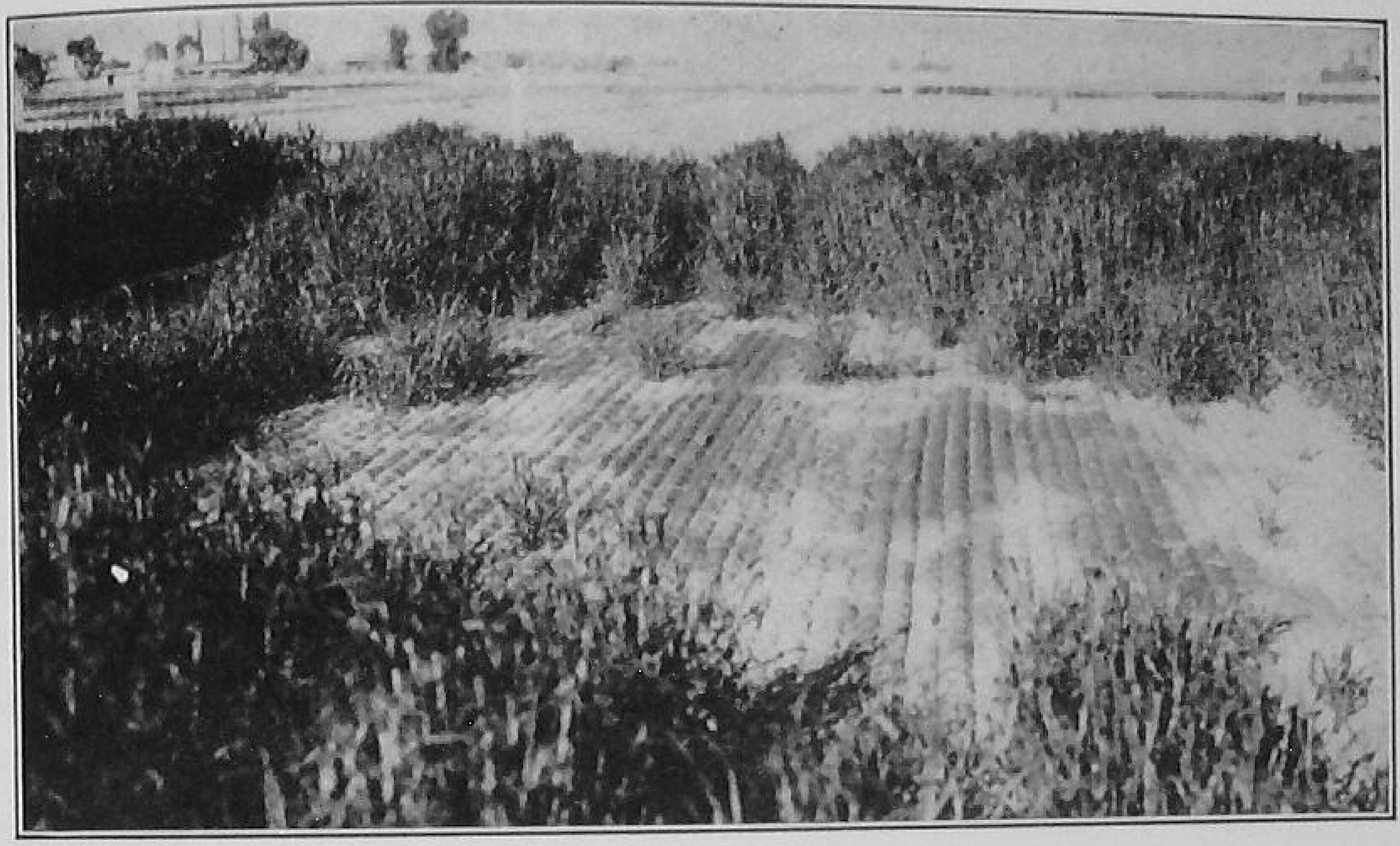


FIG. 141. Excessive soil salinity prevents barley growth. (*U.S.D.A. Circ.* 707.)

Electrical Conductivity. The reciprocal of the electrical resistivity. The resistivity is the resistance in ohms of a conductor which is 1 cm long and has a cross-sectional area of 1 sq cm. Hence electrical conductivity is expressed in reciprocal ohms per centimeter or mhos per centimeter. The terms "electrical conductivity" and "specific electrical conductance" have identical meaning.

Equivalent Weight (or combining weight with hydrogen). Atomic or formula weight divided by its valence. For example:

$$Na^+ = \frac{23}{1} = 23 \qquad Ca^{++} = \frac{40}{2} = 20$$

$$Cl^- = \frac{35.5}{1} = 35.5 \qquad SO_4^{=} = \frac{96}{2} = 48$$

Exchangeable-Sodium Percentage. Degree of saturation of the soil-exchange complex with sodium, defined as follows:

$$ESP = \frac{\text{Exchangeable sodium (milliequivalents per 100 gm soil)}}{\text{Cation-exchange capacity (milliequivalents per 100 gm soil)}} \times 100$$

Non-Saline-Alkali Soil. Soil for which the exchangeable-sodium percentage is greater than 15, and the conductivity of the saturation extract is less

than 4 millimhos per centimeter (at 25° C). *p*H values for these soils generally range between 8.5 and 10.

Saline-Alkali Soil. A soil for which the conductivity of the saturation extract is greater than 4 millimhos per centimeter (at 25° C), and the exchangeable-sodium percentage is greater than 15. The *p*H of the saturated-soil paste may somewhat exceed 8.5.

Saline Soil. A soil for which the conductivity of the saturation extract is greater than 4 millimhos per centimeter (at 25° C), and the exchangeable-sodium percentage is less than 15. The *p*H of the saturated-soil paste is usually less than 8.5.

Soil Reaction, pH. The *p*H scale is a measure of the effective concentration of the hydrogen ion. It has long been used as an index of the acidity or alkalinity of soils. A *p*H value of 7.5 to 8.0 usually indicates the presence of carbonates of calcium and magnesium, and a *p*H of 8.5 or above usually indicates appreciable exchangeable sodium.

Reference to these terms and definitions will be helpful in a study of this chapter.

174. Saline Soils For saline soils the electrical conductivity of the saturation extract is more than 4 millimhos per centimeter, and the exchangeable-sodium percentage is less than 15. These soils correspond to Hilgard's "white alkali" soils. When adequate drainage is established and the soluble salts are removed by leaching they become normal soils, that is, non-saline.

Saline soils may develop from normal soils through the accumulation of salts from applied irrigation water, or by upward-moving ground water, or by a combination of both processes.

The chemical characteristics of saline soils are determined by the kinds and amounts of salts present which largely control the concentration and osmotic pressure of the soil solution. Sodium seldom comprises more than half of the soluble cations and hence is not absorbed to any appreciable extent. The relative amounts of calcium and magnesium in the soil solution may vary considerably. Soluble and exchangeable potassium are ordinarily only minor constituents but may occasionally occur in excess. The chief anions are chloride, sulfate, and sometimes nitrate. Small amounts of bicarbonate may occur, but, because the *p*H is 8.5 or less, soluble carbonates are usually absent. In addition to the readily soluble salts, saline soils may contain relatively insoluble salts such as calcium sulfate (gypsum) and calcium and magnesium carbonates.

Owing to the presence of excess salts, and absence of appreciable exchangeable sodium, the colloids in some saline soils are highly flocculated, thus providing a favorable structure and improved per-

meability to water and air. However, some saline soils have very low permeabilities.

Analyses of some soils by the Salinity Laboratory are presented in Table 32. The *p*H of saturated soil, exchangeable sodium, electrical conductivity, and other properties are presented for normal soils, saline soils, saline-alkali soils, and non-saline alkali soils. The next two articles describe further the classes of soil included in Table 32.

175. Saline-Alkali Soils Soils for which the conductivity of the saturation extract is greater than 4 millimhos per centimeter, and the exchangeable-sodium percentage is greater than 15 are designated saline-alkali soils. As long as excess salts are present the appearance and properties of these soils are generally similar to those of saline soils. Under conditions of excess salt the *p*H value is seldom higher than 8.5, and the colloids remain flocculated. If the excess soluble salts are temporarily leached downward, the properties of these soils may change markedly (unless gypsum is present) and become similar to those of non-saline-alkali soils. As the concentration of the salts in the soil solution is lowered, some of the exchangeable sodium hydrolyzes and forms sodium hydroxide. The sodium hydroxide may change to sodium carbonate upon reaction with carbon dioxide. The soil then usually becomes strongly alkaline (*p*H above 8.5), the colloids disperse, and the soil develops a structure unfavorable for water infiltration and percolation, and for tillage. Although the return of the soluble salts may lower the *p*H value and restore the colloids to a flocculated condition the management of saline-alkali soils continues to be a problem until the excess salts and exchangeable sodium are removed from the root zone.

176. Non-Saline-Alkali Soils When the exchangeable-sodium percentage of soils is greater than 15 and the conductivity of the saturation extract is less than 4 millimhos per centimeter, the *p*H values generally range between 8.5 and 10 and the soils are designated non-saline-alkali soils. These soils correspond to Hilgard's "black alkali" soils. They frequently occur in semiarid and arid regions in small irregular areas, which are referred to as "slick spots." Except when gypsum or another source of soluble calcium is present, the drainage and leaching of saline-alkali soils develops non-saline-alkali soils. The removal of the excess salts in such soils permits hydrolysis of the exchangeable sodium and may lead to the formation of small amounts of sodium carbonate. The soil organic matter is highly dispersed and distributed over the soil particles, thereby darkening the

TABLE 32

ANALYSES OF SOILS FROM WESTERN UNITED STATES BY THE UNITED STATES REGIONAL SALINITY LABORATORY

Soil Determination								
Depth in Inches	Soil Reaction, *p*H of Saturated Soil	Saturation Percentage	Exchangeable Na m.e. per 100 gm	Exchangeable Capacity m.e. per 100 gm	Exchangeable Na Percentage	Gypsum m.e. per 100 gm	Laboratory Permeability, in. per hr Initial	Laboratory Permeability, in. per hr Final
				Normal Arid Soils				
0–12	7.8	28	0.1	12.5	0.8	0.0	....	....
0–12	8.2	41	0.2	6.9	2.9	0.0	....	....
0–12	8.0	59	2.7	22.6	11.8	0.0	....	....
				Saline Soils				
0–6	8.0	46.5	1.3	17.0	7.7	0.0	0.15	0.08
0–8	7.8	50	1.1	9.7	11.4	0.0	1.14	0.86
0–12	8.0	40	1.9	18.6	10.2	...	....	....
				Saline-Alkali Soils				
0–6	8.4	38.7	5.9	15.7	37.6	24.4	0.60	0.53
0–6	9.1	46.9	8.6	22.0	39.0	0.0	0.05	0.05
0–8	8.9	43.8	6.3	10.8	58.5	0.0	0.01	0.001
0–12	9.3	35.8	16.4	26.2	62.6	0.0	0.06	0.02
				Non-Saline-Alkali Soils				
6–12	9.2	61.9	12.5	31.7	39.4	0.0	0.22	0.25
0–12	7.6	44.0	7.4	32.5	22.8	0.0	0.08	0.01
0–12	8.7	25	4.2	18.8	22.5	0.0	....	....

SATURATION EXTRACT DETERMINATIONS

Electrical Conductivity, Millimhos/cm	Soluble Cations m.e./liter				Soluble Anions m.e./liter				
	Ca	Mg	Na	K	CO_3	HCO_3	SO_4	Cl	NO_3
					Normal Arid Soils				
0.9	6	2	1	1	0	4	2	2	Trace
1.3	8	1	4	1	0	4	7	3	Trace
2.4	2	2	18	1	0	5	15	3	1
					Saline Soils				
12.0	37	34	79	1	0	7	62	47	32
12.2	57	32	56	1	0	2	44	73	48
8.8	28	23	53	1	0	5	74	29	Trace
					Saline-Alkali Soils				
47.9	30	62	668	3	0	12	524	180	50
20.4	2	1	188	42	0	16	131	93	Trace
19.3	7	6	234	2	0	3	222	38	4
5.6	1	1	59	2	5	20	22	46	Trace
					Non-Saline-Alkali Soils				
2.8	2	1	28	2	1	15	14	3	Trace
1.6	1	1	14	1	—	—	—	—	—
1.2	2	1	11	2	1	10	1	1	Trace

color. When the soil contains appreciable organic matter its surface may be quite dark, hence the term "black alkali."

Partially sodium-saturated clay in the absence of flocculating salts is highly dispersed and has a tendency to migrate downward through the soil and accumulate at lower levels. As a result the surface few inches of the soil may be relatively coarse in texture and friable; but, below where the clay accumulates, the soil develops a dense layer of low permeability. Alkali soils commonly develop in some valleys as a result of irrigation. The physical and chemical properties of non-saline-alkali soils are largely determined by the exchangeable sodium present. As the proportion of exchangeable sodium increases, the soil tends to disperse more and the *p*H value increases, becoming as high as 10. The soil solution of non-saline-alkali soils, although relatively low in soluble salts, has a composition which differs greatly from that of normal and saline soils. The anions present consist mostly of chloride, sulfate, and bicarbonate, but small amounts of the normal carbonate usually occur. At high *p*H values, and in the presence of normal carbonate, calcium and magnesium are precipitated so that the soil solutions of non-saline-alkali soils usually contain only traces of these cations, sodium being the predominant one. Considerable amounts of exchangeable and soluble potassium occur in some alkali soils.

177. Movement of Salts in Soils If it were possible to maintain a moisture distribution in irrigated soils such that water flow would be continuously downward there would be relatively little trouble from salinity on irrigated farms. A continuous downward flow of water with adequate drainage would gradually decrease the soluble salts in the upper few feet of soil, in which plants obtain most of their moisture and food. However, in the absence of adequate drainage, downward percolating waters fill the lower soil spaces and cause the water table to rise. During periods between irrigations a high water table favors the upward capillary flow of water to the land surface, where it evaporates. The soluble salts carried by the upward-moving water cannot be evaporated, and hence they are deposited on or near the soil surface. Salts so deposited may come from soil horizons well below the surface that contain high percentages of salts. The mere concentration on the surface of the salts that normally occur distributed through the upper few feet of soil may cause serious salinity.

178. Influence of the Water Table The influence of a rising water table on the upward capillary flow is analogous to the influence of making a canal grade steeper and steeper: both cause an increase in

the velocity of the flowing water. A review of Chapter 10 will enable the student to see more clearly how the position of the water table influences the hydraulic slope and hence the upward flow of soil water. A high water table increases the moisture content of the unsaturated surface soil and thus increases the permeability and the quantity of flow. The soluble salts are held near the surface of the body of ground water where they may readily be drawn by upward capillary flow to the soil surface and there deposited as the water evaporates.

As the water lowers, some of the salts in the free water are retained by the soil so that the free water gradually becomes less saline. The kind and quantity of salts in the soil solution usually differ from those found in the free ground water or from the alkali incrustations on top of the soil. Because of differences in solubility certain of the soluble salt ions are absorbed by the soil, while others move somewhat more freely. Calcium sulfate may be abundant in the soil solution with magnesium sulfate second, while sodium sulfate forms much of the effervescent matter on the surface, and the salts next to the surface. Sodium chloride does not separate as readily as some of the other salts.

Irrigation farmers sometimes urge the advantages of keeping the water table within a few feet of the soil surface because of the high crop yields obtained during the early years after it has risen from great depths. The favorable moisture supply from a water table near the soil surface may cause high crop yields, but, as a rule, in areas where alkali salts occur, the temporary favorable condition of the high water table is followed by serious decrease in yields, if not by complete non-productivity due to salt concentration. The need for prevention of excessive seepage losses from canals by canal linings described in Chapter 4 is great. Careful and efficient application of water on the farms in order to delay as far as possible the time of the rise of the water table and also provision of artificial drainage on areas for which natural drainage is inadequate to keep the water well below the soil surface are very urgent and not likely to be overemphasized.

179. Reducing Evaporation The first and most important single step in reducing evaporation from irrigation soils is to keep the water table well below the land surface either by efficient application of irrigation water, or by drainage, or both.

However, certain additional factors tend to favor excessive evaporation, of which the following are noteworthy: (*a*) unduly frequent irrigation, thus keeping the surface wet during a proportionately long

time, and (*b*) direct exposure of the land surface to sunlight by lack of cropping. As a rule, on all irrigated soils, it is good practice to apply enough water in a single irrigation to fully moisten the soil to the depth from which plant roots have taken the moisture previously in the soil. This depth ranges from 2 to 6 ft approximately, depending on the crop, and the texture, structure, and depth of the soil. In the management of saline and alkali soils it is especially important to moisten the soil at each irrigation to the full depth that it needs additional moisture, in order to reduce the frequency of irrigation and thus reduce the upward flow and evaporation of water.

An effective mulch, by adding copious quantities of barnyard manure, straw, or other vegetative material, does much to reduce evaporation. Manure is especially valuable in alkali land because of benefits in addition to reducing evaporation. Retarding evaporation from alkali soils is urgently necessary. It is well also to maintain, as far as practicable, a growing crop as a means of absorbing the water and of shading the soil, thus reducing evaporation.

180. Methods of Temporary Control Temporary control of salts on irrigated land is sometimes practiced by one or more of the following methods:

(*a*) Plowing salt surface crusts deeply into the soil.
(*b*) Removing surface accumulation from the soil.
(*c*) Neutralizing the effects of certain salts by use of other salts or acids.

For detailed consideration of these methods the student is referred to *Soil Alkali* by Harris, *Saline Soils and Their Management* by Curry, and to the publications of the University of California and the United States Regional Salinity Laboratory.

181. Steps Essential to Reclamation Permanent reclamation of alkali land requires four essential steps and the attainment of four basic conditions, namely:

(*a*) Adequate lowering of water table.
(*b*) Satisfactory water infiltration.
(*c*) Leaching excess salts out of the soil.
(*d*) Intelligent management of the saline and alkali soils.

182. Adequate Lowering of Water Table All waterlogged lands, whether or not impregnated with alkali, are improved for ordinary crops by lowering of the water table. This means a permanent lowering under the farmer's control so that a rise of water above a given elevation in the soil for any length of time may be wholly prevented. The

first step in lowering the water table is to learn the *source* of the water that caused it to rise. In isolated cases on small tracts it is sometimes possible for one farmer alone, or a small group of farmers, to find the water source and cut it off by construction of one or more intercepting ditches. Usually, in irrigated regions, small waterlogged areas are caused by water flowing to them from higher irrigated lands, above or underground, or from canals, ponds, or reservoirs. The farmer whose holdings are located within large areas of comparatively level waterlogged land cannot, as a rule, lower the water table by his own efforts. For such areas community action is essential. Problems and procedures in the drainage of irrigated lands are considered in Chapter 12.

183. Satisfactory Infiltration Rates The rate of water infiltration into soils depends on soil texture, structure, degree of dispersion, and also on the depth to the water table. When adequate drainage has been provided, the structure of the soil and other properties are dominant in influencing infiltration. The time required for an adequate depth of water to percolate through the soil may well limit the feasibility of reclamation.

Alkali soils disperse during leaching and often become impermeable as the soluble salts are removed. Chemical amendments are then required to bring about improvement of the soil by replacing the exchangeable sodium with calcium. Gypsum, and, under certain conditions, sulfur, may be used for this purpose, but reclamation is more rapid when gypsum is applied. Considerable gypsum occurs naturally in the soils of some areas, but the amount and distribution within the soil profile are variable.

Reeve, Allison, and Peterson, in a 2-year study of leaching saline-alkali soils in the Delta Area, Utah, found infiltration rates during the first hour of measurement on three different experimental plots ranging from 1.2 up to 6.3 in. per hr. After 48 hr of leaching the rates ranged from 0.21 to 0.57 in. per hr. The Salinity Laboratory designates permeabilities of 0.1 up to 0.3 in. per hr as ranging from unsatisfactory to good; from 0.3 to 3.0 in. as good, and above 3 in. as excessive.

Information on the rates at which water enters and moves through the soil is useful in connection with irrigation methods as well as improvement of saline and alkali soils. Many factors which are not yet fully understood and correlated influence these rates, but it is not difficult to make measurements that have practical significance. Infiltration and permeability are expressed in terms of the velocity of water flow, and for soils work are usually reported either in inches per hour or feet per year.

Infiltration rates are generally measured in the field. The principal method is flooding or impounding water on the soil surface. Infiltration measurements have been made in connection with basin irrigations and leaching of soluble salts.

Water of the same quality as irrigation or leaching water should be utilized for infiltration tests in the field, otherwise the measurements may be misleading. The length of time the test should be conducted or the depth of water to be applied will depend on the purpose of the test and the kind of information sought. If it is a matter of appraising an irrigation problem, then the depth corresponding to one irrigation may be sufficient. If getting advanced information on infiltration for planning a heavy leaching program is involved, then the full leaching depth is recommended. It often happens that subsurface drainage in the soil is sufficiently slow to reduce infiltration rates considerably. Although small-area tests will give useful information on infiltration during leaching, the infiltration values thus obtained will apply to large areas only if underdrainage is adequate.

Permeability as measured in the laboratory is influenced by many factors. Some of these, such as dispersion of the soil, base status, air saturation, and microbial sealing, have been separately studied and partially appraised. The structure and packing of the sample enter directly into the measurement. It appears that air-dried and screened samples may be used if interest is centered primarily on the cultivated layer. Natural structure may be required for significant measurements on the subsurface layers.

184. Leaching Excess Salts It is usually essential that large depths of water be applied to alkali lands and made to percolate through the soil in order to leach out the excess salts. Coarse-textured soils of open structure as a rule have sufficiently high permeability to make leaching of alkali salts an easy task after the water table has been sufficiently lowered. Fine-textured compact soils of low permeability predominate in the low-lying waterlogged areas. Consequently, soil permeability is a factor of paramount importance in the leaching of excess soluble salts from most waterlogged soils. Permeability is influenced not only by the texture and compactness of the soil but also by flocculation or dispersion of the soil particles. The dispersion and, consequently, the permeability are greatly influenced by certain chemical compounds. A very low permeability sometimes follows the leaching of alkali salts, and this decreases the productivity of the soil because of the difficulty of getting air and water to penetrate it.

Curry reports that leaching tests on 11 farms in Rio Grande Valley

near El Paso having sandy loam and silt-loam soils greatly reduced the salt content of the soils and increased the production of alfalfa, corn, cotton, and cane. The tests were made on areas ranging from 5 to 30 acres for each farm, the total area for all the farms being 176 acres. Depths of water applied ranged from 2 ft to 5 ft.

In the study of the reclamation of saline-alkali soils in the Delta Area, Utah, Reeve, Allison, and Peterson found that leaching was very effective where the depth of water table provided ample opportu-

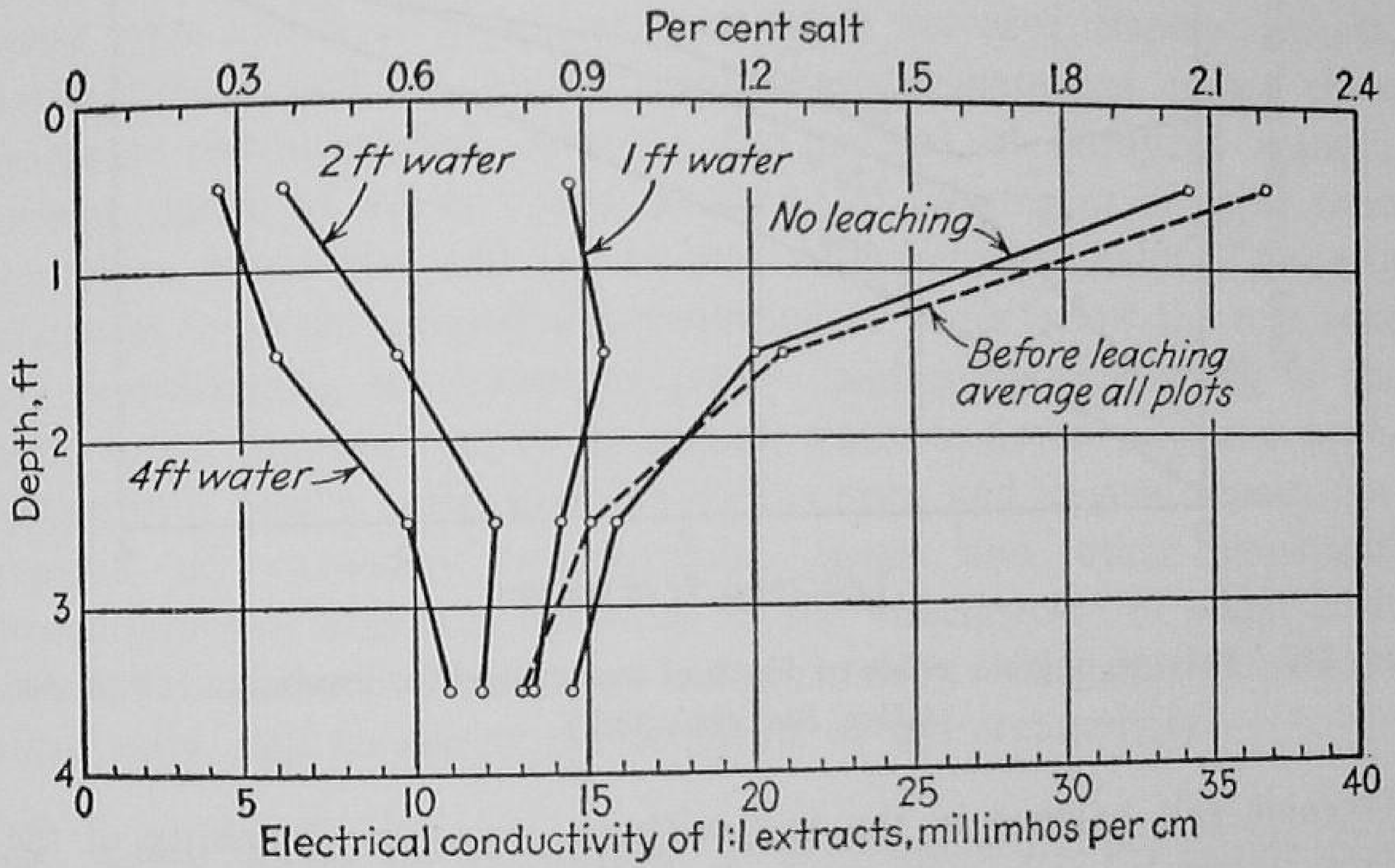


FIG. 142. Salt distribution in soil profile before and after leaching at site *A*, showing effect of three leaching treatments. (*Utah Agr. Exp. Sta. Bul.* 335.)

nity for the water applied to the experimental plots to percolate below the 4-ft-depth root zone. The effectiveness of the leaching at one of the experimental sites, *A*, as measured by the reduction of salt content of the soil is presented in Fig. 142 for each of three depths of water applied: 1, 2, and 4 ft. The surface foot of soil, for example, contained 2.2 percent of salts before leaching and less than 0.3 percent after leaching with 4 ft of water.

The effectiveness of leaching on the yield of grain in bushels per acre for each of the three experimental sites is shown by the curves of Fig. 143. At site *A*, for example, the yield was increased from about 12 bu per acre with 1-ft depth of water up to more than 40 bu with 4 ft. Without leaching the land was barren.

Maintaining a favorable salt balance in the soil requires proper and efficient irrigation methods. Irrigation must provide water for growth of crops and at the same time allow enough water to pass through

the soil to leach out the excess salts. Excessive leaching, however, may be detrimental in that plant nutrients, especially nitrates, may be removed from the soil. Over-use of water also adds to the drainage problem. A happy medium must be reached by efficient irrigation methods where water applications are just sufficient to maintain a

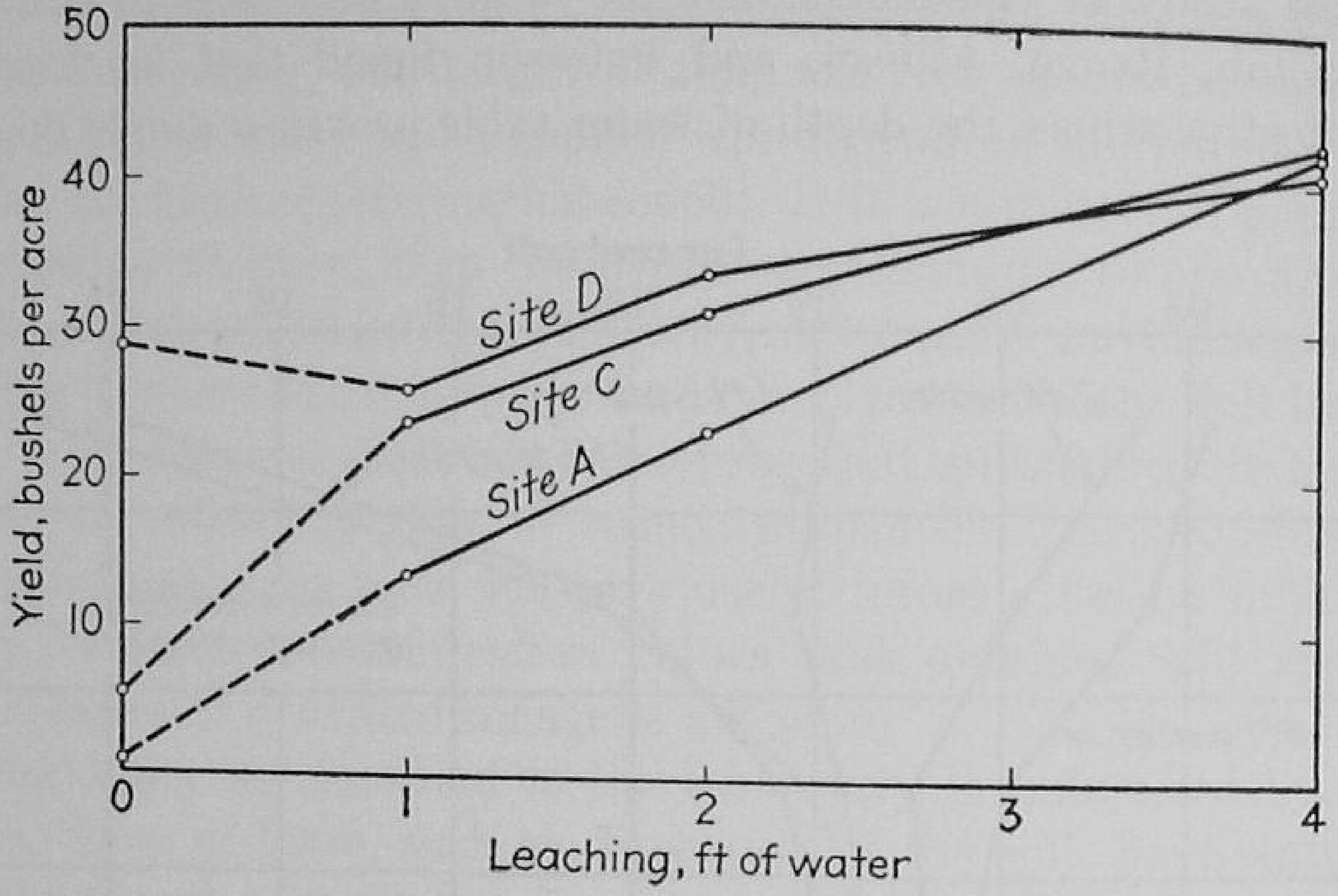


FIG. 143. Relation of grain yields to depth of water used for leaching. (*Utah Agr. Exp. Sta. Bul.* 335.)

favorable salt balance in the soil without excessive leaching of the plant nutrients and without materially adding to the drainage problems.

185. Reclamation and Management of Saline and Alkali Soils Sometimes irrigation farmers who own alkali land on which the water table has been adequately lowered, and from which the excess alkali salts have been leached, erroneously conclude that the task of reclamation has been completed. Reclamation is attained only when the lands are made to produce large crop yields. Usually the restoration of full productive capacity, or its establishment in virgin alkali lands, requires both chemical and physical improvements in the soils.

Alkali soils usually contain excessive amounts of sodium, held by the finer soil particles, and therefore have a poor physical condition. To reclaim these soils they must be changed chemically and improved physically.

The chemical changes consist in exchanging calcium for sodium and then leaching away the sodium salts. Any soluble calcium compound will do, and the greater the concentration of calcium in the reclamation water, or in the soil solution bathing the soil particles during reclama-

tion, the more rapidly this process will take place. If the soil does not contain gypsum it can be added and dissolved by irrigation water. Other soluble calcium compounds such as calcium chloride are also very helpful but are expensive.

Studies of a number of alkali soils have been made at the United States Regional Salinity Laboratory using pot tests to diagnose the soil condition and to determine the effect of chemical treatments. On the basis of such tests recommendations are made for field studies. Some alkali and saline soils are low in available phosphorus and will give better crop yields if phosphate fertilizers are used. Superphosphate, treble superphosphate, and ammonium phosphate are among those generally recommended. Liberal applications of barnyard manure, plowing under of cover crops, avoiding of plowing or of other farm operations when the soil is too wet—all these are helpful. Care in irrigation to avoid excessive percolation of water below the root zone and overcharging of drains or pumps and consequent rising of the water table, but still applying enough water to assure adequate penetration into heavy soils, keeping drains open and in good repair, prevention of excessive evaporation—these and other important precautions are urgently essential to the management of alkali lands in order to assure permanent relief from waterlogging and excess alkali salts, and to assure perpetuation of soil productivity.

186. Saline Water for Irrigation It is probable that population pressures and public welfare will require the utilization of all the available water in the arid regions of the world. Domestic water supplies are of first importance, and next in importance are the uses for irrigation and for industrial purposes. Proper quality of water is essential to satisfactory domestic use and irrigation. Nearly 200 million acres of the world's agricultural lands are being irrigated. The intensity of demand for water is greater in some irrigated sections than in others, but in only a very few of the arid regions of the world is the total water supply, when fully stored and controlled, large enough to fully irrigate all the arable land. In some sections, notably the Sevier River area in Utah, and parts of California, all the available water is used and the so-called saturation point of irrigation expansion has been reached.

As the saturation point in irrigation expansion is approached the urge to use saline waters is increased. However, excessive amounts of salts in the irrigation water result in fatality to crops and financial losses to water users. On the other hand, small amounts of salts in water not only are harmless but actually stimulate crop growth under some conditions. A study of the safe limits of salts in irrigation water,

and of the conditions under which saline water may best be used for irrigation, is essential to complete an intelligent utilization of arid-region resources.

187. Typical Analyses of Irrigation Waters The analyses of selected irrigation waters shown in Table 33 bring out the following points.

The Rio Grande at Del Norte, Colorado, sample 1, represents a mountain water low in total salts and high in the percentage of bicarbonate. Sample 2, taken from the same river in southern New

TABLE 33

ANALYSES OF SELECTED IRRIGATION WATERS

Sample	Source	Specific Electric Conductance ($K \times 10^5$ at 25° C)	Concentration		Constituents (m.e. per liter)								Sodium, %	Boron, ppm
					Cations (bases)				Anions (acids)					
			Per Acre-Foot, tons	Total Solids, ppm	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3		
1	Rio Grande, Colorado	8.5	0.1	81	0.56	0.27	0.30		0.70	0.32	0.12	[2]	26	
2	Rio Grande, New Mexico	87.0	.8	641	3.76	1.34	4.03		2.97	4.69	1.53		44	
3	Pecos River, Texas	915.0	8.4	6,198	30.62	17.19	53.62			44.52	54.00		52	
4	Snake River, Idaho		.5	380	2.60	1.80	1.74	0.14	3.28	1.69	1.18	0.04	28	
5	Colorado River, Arizona	113.5	1.1	795	5.08	2.21	4.54		2.56	6.97	2.31	.04	35	0.14
6	Well in Coachella Valley, California	174.0	1.2	910	2.14	.08	12.67		1.02	1.80	12.04	.14	85	.71

Mexico, shows the increase in concentration between Colorado and New Mexico, and the increasing proportion of sodium, chlorides, and sulfates.

Sample 3, from the Pecos River near Barstow, Texas, is an example of one of the most concentrated waters used for irrigation purposes. The water is applied to a soil high in gypsum. Fair to good crops of cotton and alfalfa are obtained.

Sample 4, from the Snake River, Idaho, is representative of irrigation waters in the Northwest. They are, as a whole, low in total salt content.

Sample 5, from the Colorado River, Arizona, was selected to show the type of irrigation water run onto fairly heavy soil in the Imperial Valley. The water contains 1.1 tons of salt per acre-foot, which is a little more than the average for irrigation water.

Sample 6, from an irrigation well, was selected as a water of high sodium percentage. Used on sandy soils it does some injury to grapes. The boron content is rather high.

188. Standards for Irrigation Waters Plants in saline soils are adversely affected by high concentrations of salts in the soil solution and by poor physical condition of the soil. Both soil conditions are affected by the irrigation water. An irrigation water having a high sodium percentage will, after a time, give rise to a soil having a large proportion of replaceable sodium in the colloid, often designated as black alkali soil. Even on sandy soils with good drainage, waters of 85 percent sodium* or higher are likely to make soils impermeable after prolonged use. With higher total salt content there is a flocculating action that tends to counterbalance the poor physical condition caused

TABLE 34

Standards for Irrigation Waters

Water Class	Conductivity ($K \times 10^5$ at 25° C)	Salt Content		Sodium, %	Boron, ppm
		Total, ppm	Per Acre-Foot, tons		
1	0–100	0–700	1	60	0.0–0.5
2	100–300	700–2000	1–3	60–75	0.5–2.0
3	Over 300	Over 2000	Over 3	75	Over 2.0

by a high sodium concentration in the water. On a heavy soil already high in replaceable sodium the poorest water would be one low in total salts but having a high sodium percentage.

The concentration of the soil solution also modifies plant growth and is usually 2 to 100 times the irrigation-water concentration, and seldom more dilute. In heavily irrigated sandy soils the soil solution will tend to approach the same concentration as that of the irrigation water. On heavy soils, where evaporation may greatly exceed drainage, the concentration of the soil solution may be 100 times that of the irrigation water and become too great for plant growth.

In most arid-region valleys neither the irrigation companies nor farmers can modify their irrigation water to any substantial degree. However, the standards for waters presented in Table 34 should assist interested agencies in appraising and developing irrigation and drainage practices to harmonize with qualities of water.

Class 1 waters are considered by the Salinity Laboratory Staff as excellent to good, suitable for most plants under most conditions.

Class 2 as good to injurious, probably harmful to the more sensitive crops. Also the laboratory considers class 3 waters injurious to unsatis-

* Percent sodium $= \dfrac{100 \text{ Na}}{\text{Ca} + \text{Mg} + \text{Na} + \text{K}}$.

factory, probably harmful to most crops. Class 3 waters are considered unsuitable under most conditions.

If the salts present are largely sulfates the values for salt content in each class can be raised 50 percent. Because soil, crop, climate, drainage, and soil management all influence the suitability of water for irrigation, no simple classification scheme will hold for all cases.

Some writers have indicated that waters of 70 percent sodium are unsuitable under most conditions, and a few have suggested an even lower limit. Yet on sandy soils in the Coachella Valley, California, waters of more than 80 percent sodium are used and the farmers stay in business. For class 3 waters a low limit sodium percentage of 75 has therefore been selected. Scofield, Wilcox, and Magistad have selected a specific electrical conductivity ($K \times 10^5$) of 300 as being the upper limit for good production on most soils and waters. A marked exception occurs in the Pecos Valley, where good growth of alfalfa and cotton was found on lands irrigated with water having a conductance of 915. The Pecos Valley may be considered special because of the heavy soil content of gypsum and lime.

The boron content of a water is of great importance for many crops. Some crops, as beans, are very sensitive to an excess of boron, and others, as sugar beets, will tolerate large quantities. A water containing more than 2.0 ppm will in time usually cause trouble with many of the crops grown.

189. Sources of Salinity in Water Salinity in irrigation water that is obtained from gravity canals originates in one or more of three sources, namely:

(*a*) In the natural drainage water yielded by watersheds that contain large amounts of alkali salts in the soils and rocks; or

(*b*) In the conveyance of rivers or canals through soil or rock formations that are highly impregnated with alkali salts; or

(*c*) In the diversion of canals from the lower reaches of streams and rivers that receive large quantities of seepage and return flow from irrigated lands.

The amounts of salts in natural drainage water near the stream sources are usually so small as to be of little concern. However, the Malad River in southern Idaho and northern Utah, a small stream, contains so large an amount of soluble salts that the application of its water for irrigation early proved seriously harmful to trees and general farm crops. In the Uintah Basin, Utah, irrigation water that was almost entirely free from salts at the diversion works absorbed

excessive amounts as it was conveyed through canals constructed in beds of Mancos shale.

The greater and more dangerous source of salts in irrigation water is from seepage and return flow. This fact is illustrated by a study of the salt content of water at different points along rivers that traverse

TABLE 35

INCREASE IN THE SALT CONTENT OF THE WATER IN TYPICAL WESTERN RIVERS DUE TO SEEPAGE AND RETURN FLOW OF WATER FROM IRRIGATED LANDS, AS SUMMARIZED BY HARRIS

River	State	Salt Content, ppm		Increase, ppm	Distance, in miles	Increase per mile, ppm
		Upper	Lower			
	Colorado	110	1178	1068	20	53.4
Jordan	Utah	890	1970	1080	14	77.0
Sevier	Utah	205	831	626	60	10.4
Sevier	Utah	205	1316	1111	150	7.4
Pecos	New Mexico	760	2020	1260	30	42.0
Pecos	New Mexico	760	5000	4240	180	24.1
Arkansas	Colorado	trace	2200	2200	120	18.3

irrigated lands and receive return seepage waters. Table 35 reporting some determinations of total alkali salts in five western rivers at points separated from 14 to 180 miles shows appreciable increases in alkali from the higher to the lower points. The maximum increase per

TABLE 36

SEASONAL VARIATION OF TOTAL SALT CONTENT OF TYPICAL WESTERN RIVERS. AMOUNTS OF SALTS EXPRESSED AS PARTS PER MILLION OF WATER (PPM)

Salt River, Arizona	ppm	Gila River, Arizona	ppm	Sevier River, Utah	ppm
Aug. 1–Sept. 1, 1899	724	Nov. 28, 1899–Jan. 18, 1900	1168	July 29	958
Sept. 2–Sept. 9, 1899	1100	Feb. 1–Mar. 7, 1900	1136	Aug. 12	1104
Sept. 10–Oct. 9, 1899	1142	Aug. 1–Aug. 14, 1900	541	Aug. 24	1268
Oct. 10–Oct. 17, 1899	952	Aug. 15–Aug. 28, 1900	925	Sept. 18	1190
Oct. 18–Dec. 30, 1899	1026	Sept. 1–Sept. 28, 1900	471	Sept. 21	1426
Feb. 17–May 30, 1900	1069	Sept. 29–Nov. 5, 1900	1085	Oct. 5	1406
June 1–Aug. 4, 1900	1391			Oct. 19	1436
				Nov. 9	1376

mile, 77.0 ppm, occurred in the Jordan River, Utah, and the minimum in the Sevier River, also in Utah. The owners of irrigation projects that divert water from the lower reaches of streams that receive seepage and return flow from upstream alkali lands should know the salt

TABLE 37

TOLERANCE OF THREE TYPES OF CROPS FOR SALINITY AS DETERMINED BY THE UNITED STATES REGIONAL SALINITY LABORATORY

Under each of the three types of crops the most tolerant crops are listed first and the least tolerant last.

Type of Crop	Salt Tolerance			
	Good (Group I)	Moderate (Group II)		Poor (Group III)
Fruit	Date palm	Pomegranate Fig Grape Olive		Grapefruit Pear Almond Apricot Peach Plum Apple Orange Lemon
Field and truck	Sugar beet Garden beet Milo Rape Kale Cotton	Alfalfa Flax Tomato Asparagus Foxtail millet Sorghum (grain) Barley (grain) Rye (grain) Oats (grain) Rice	Cantaloupe Lettuce Sunflower Carrot Spinach Squash Onion Pepper Wheat (grain)	Vetch Peas Celery Cabbage Artichoke Egg plant Sweet potato Potato Green beans
Forage	Alkali sacaton Salt grasses Nuttall alkali Bermuda Rhodes Rescue Canada wild rye Beardless wild rye Western wheat grass	White sweet clover Yellow sweet clover Perennial rye grass Mountain brome Barley (hay) Birdsfoot trefoil Strawberry clover Dallis grass Sudan grass Hubam clover Alfalfa (California common) Tall fescue Rye (hay)	Wheat (hay) Oats (hay) Orchard grass Blue grama Meadow fescue Reed canary Big trefoil Smooth brome Tall meadow oat grass Cicer milk vetch Sour clover Sickle milk vetch	White Dutch clover Meadow foxtail Alsike clover Red clover Ladino clover Burnet

content of the water and, if necessary, take special precautions to avoid injury to crops and soils from this source of alkali.

The salt content of irrigation water in the several streams of the West varies appreciably from one part of the irrigation season to another, as is shown by the data of Table 36.

190. Tolerance of Crops to Salinity Some plants can stand waterlogged soils for short periods while others cannot survive under the same conditions. For soils having a high water table, as well as salinity, plants should be selected which can tolerate the waterlogged soils as well as excess salts. Strawberry clover, Bermuda grass, and sweet clover owe part of their popularity to this characteristic.

Selection of salt-tolerant crops depends on the intended use of the crop, the moisture conditions of the soil, the climate, farm-management practices, and other local factors.

Three general tolerance groups are listed by the Regional Salinity Laboratory. Group I includes those plants which have good tolerance; group II, moderate tolerance; and group III, poor or slight salt tolerance.

The plants listed in Table 37 have been classified into three broad divisions: namely (1) common fruit and vine crops, (2) field and truck crops, and (3) forage crops such as grasses, legumes, and cereals which are used primarily for pasture or hay production. Group II crops require a more intensive type of farming than the group III forage plants, and yet they differ from the fruit crops of group I.

In each group the plants first named are considered to be more tolerant and the last-named more sensitive to salinity. The opinion that further research in crop tolerance to waterlogging and salinity is essential to making the classification as presented in Table 37 more complete and more nearly final is emphasized by the Laboratory.

12

Drainage of Irrigated Lands

Adequate drainage of crop-producing lands requires a general lowering of shallow water tables. Some students, especially in humid regions, find it difficult to think of drainage being essential in arid regions where irrigation is required for crop production. Experience has demonstrated fully the need for drainage of irrigated lands. In some valleys the higher lands never require drainage, but the need for drainage of the lower valley lands is frequently a result of the irrigation of the higher lands. From 10 to 20 percent of the irrigated lands in arid regions need drainage to perpetuate their productivity. The reclamation of saline and alkali soils has many important phases, but adequate lowering of the water table by drainage is a first and basic necessity.

Irrigation and drainage in arid regions are complementary practices, the necessity for drainage being greatly influenced by low efficiencies in the conveyance and application of irrigation water.

191. Benefits of Drainage Adequate drainage improves soil structure and increases and perpetuates the productivity of soils. Drainage is the first essential in reclamation of waterlogged saline and alkali soils. Even if only those lands which have been farmed are considered, drainage benefits irrigation agriculture and the public in many ways. For example, adequate drainage (1) facilitates early plowing and planting, (2) lengthens the crop-growing season, (3) provides more available soil moisture and plant food by increasing the depth of root-zone soil, (4) helps in soil ventilation, (5) decreases soil erosion and gullying, by increasing water infiltration into soils, (6) favors growth of soil bacteria, (7) leaches excess salts from soil, and (8) assures higher soil temperatures.

Drainage also improves sanitary and health conditions and makes rural life more attractive.

192. Areas Drained in the West Substantial progress has been made toward drainage of irrigated lands in the eleven western states. The

areas of land included in western-state drainage enterprises, together with progress toward satisfactory drainage in each of the eleven states, are presented in Table 38. More than 6 million acres are included in drainage enterprises, and 5.4 million acres have been improved by drainage sufficiently to produce normal crops according to the 1940 United States Census. In nearly all the irrigation states there are substantial areas of land unfit to produce crops because of lack of drainage. The total area in 1940 was more than 280,000 acres. The last two columns of Table 38 are of special interest, indicating that there are more than 12,000 miles of open ditches and nearly 3500 miles of tile drains.

193. Sources of Excess Water The major sources of excess water that make drainage necessary on parts of the irrigated lands are seepage losses from reservoirs or canals and deep percolation losses from irrigated lands. Efficient water application on the higher irrigated lands reduces the need for drainage of the lower lands. Flooding of lowlands due to overflow of rivers and natural drainage channels during periods of maximum stream flow constitute important sources of excess water in certain low-valley areas. The flow of ground water toward waterlogged lands in arid regions may be in any direction. In some areas flow is largely downward through highly permeable surface soils to impermeable subsoils.

In other areas unconfined or free ground water may flow under small hydraulic slopes, as illustrated in Fig. 127 (Chapter 10). In still other areas the major source of excess water may be upward flow from an artesian aquifer, as shown in Fig. 128, which is typical of large areas in several western valleys. Two or more of these possible sources of excess water contribute to the maintenance of shallow water tables in some soils. Thorough ground-water investigations and subsoil studies are essential to intelligent design of drainage systems.

Extensive use of small-diameter pipe, as piezometers described in Chapter 10, enables engineers to develop ground-water contours, or flow patterns, as shown in Fig. 144*A* and 144*B*, which indicate the directions of water flow before irrigation and after. In April, 1946, before irrigation the higher water-table elevation was only 1.5 ft above the lower, and contours were widely spaced; whereas after irrigation in May, 1948, the high water table was 4.5 ft above the lower. Between these periods of measurement the water table rose 4.0 ft in one part of the field and 1.5 ft in another. Ground-water studies illustrated by Figs. 144*A* and 144*B* are essential to intelligent

design of drainage systems. Permeability measurements are very helpful because of the great range in soil permeability. The soil permeability is the dominant variable influencing the feasibility and the cost of drainage.

Gravelly and sandy soils, under natural conditions, are from 25,000 to 50,000 times as permeable as clay soils; in some drainage studies permeability ratios of 100,000 to 1 have been measured. Subsoil formations and permeabilities thus influence sources of excess water in soils.

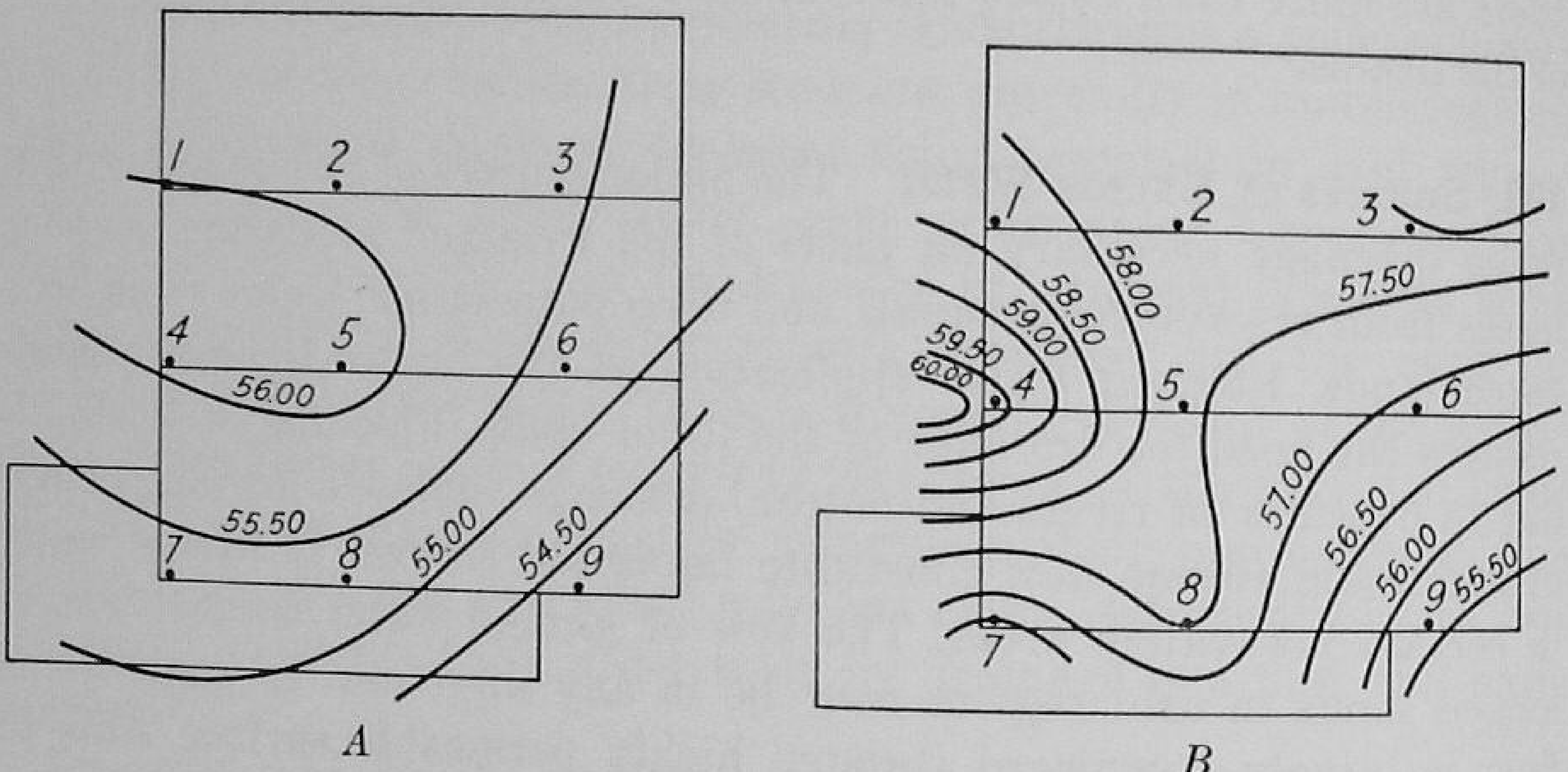


FIG. 144. U.S. Newlands Field Station. *A*. Before irrigation (April 14, 1946). *B*. After irrigation (May 12, 1948).

194. Control of Water Sources In some areas, substantial progress toward general lowering of the water table, and solution of drainage problems, can be made by control of excess water sources. For example, as stated in Chapter 4, nearly 40 percent of the water taken into canals is lost in conveyance. Millions of acre-feet thus lost annually reach the water table and cause it to rise. Lining of thousands of miles of canals to reduce these losses and remove this cause of the need for drainage should be encouraged. Accomplishment of this task of water control will require a long time.

Control of the source of excess water by percolation from the irrigated land also is a difficult and perplexing task. In a few areas, there is no excess salinity or alkali in the soil, and lowering of the water table is all that is necessary to solve the drainage problem. Lining of the irrigation canals to prevent seepage losses and the application of irrigation water by the sprinkling method to reduce or eliminate deep-percolation-water losses may result in a satisfactory lowering of the water table in these areas, thus removing the need for

drainage. This control of excess-water sources may be both impractical and prohibitive in cost in other areas, thus making drainage essential. In most arid-region waterlogged soils, leaching of soluble salts is essential to crop production, and adequate lowering of the water table by artificial drainage must precede leaching.

195. Required Water-Table Depths Adequate crop production, and perpetuation of soil fertility in irrigated areas, require water-table depths of 6 ft or more. In many cases, even where drainage systems have been installed the water table during part of the year is 3 ft or less, and this is highly undesirable. A summary of required water-table depths approved by irrigation authorities and also by financial institutions that are interested in long-time loans for improving of irrigated lands is presented.

Classification	Range in Water-Table Depths
Good	Static water table below 7 ft; up to 6 ft for a period of about 30 days of the year.
Fair	Water table at 6 ft, up to about 4 ft for a period of 30 days. No general rise.
Poor	Some alkali on surface; water table 4–6 ft up to 3 ft for a period of 30 days.
Bad	Water table less than 4 ft and rising. Natural and artificial drains too far away to drain land.

Generous long-time loans are made by land banks and other lending agencies when *good* lands are mortgaged as security; restricted or short-time loans are made on *fair* lands, and no loans at all are made on poor and bad lands. Positive assurance of immediate and adequate lowering of the water table by thorough drainage may induce financial agencies to make limited loans on *bad* lands.

196. Lowering the Water Table In arid regions the water table may be lowered by eliminating or controlling the source of excess water, improving natural drainage facilities, and providing man-made drainage systems.

Increases in the efficiencies of conveyance of water by lining canals and maintaining modern watertight take-out structures in canal banks are urgently needed. Leveling of land for irrigation and efficient design of water-application systems with more efficient application of water to farms will decrease percolation to the ground water. These needs are especially urgent on the higher lands which usually have shallow, highly permeable soils.

Proper maintenance of natural drainage systems, usually feasible at

low costs, protects irrigated lands from excess percolation of water from rains and melting snows and also from flood damages.

In many arid regions artificial drainage also is required to provide adequate lowering of the ground-water table and is accomplished by one of three methods: (*a*) open channel drains; (*b*) covered tile of clay or concrete; and (*c*) the pumping of ground water.

In open channels and tile, gravity pulls the excess water from the wet soils into the drains and gravity also causes the flow in the drains. Gravity provides the mechanical power, and the drains are designated gravity drains. When pumps are used the necessary mechanical power is obtained from electricity, gasoline, distillate, and other fuels, as in irrigation pumping considered in Chapter 5. Pumping of ground water in some valleys in arid regions provides for both irrigation and drainage.

197. Design of Open Drains On some drainage projects open drains are used largely to convey water to distant outlets. Water may flow into open drains directly from the ground water and also from collecting tile lines in many cases. The designing engineer selects the drain outlet and determines appropriate elevation of bed of drain and water surface in the drain at times of maximum flow. Then he decides the bed slope, which ranges from ½ to 1½ ft per 1000 ft. The slopes of open drains in the lower nearly level lands should be as large as the ground-surface slope provided this will not cause excessive water-flow velocities and channel erosion. Uniformity of drain-bed slope is usually advantageous even though this causes some differences in depth of drain. Design of side slopes of open drains depends largely on the soil formation, with a range from the steep slope of ½ horizontal to 1 vertical in very stiff, compact clays, to flat slopes of 3 to 1 in loose, open sandy formations. Depths of open drains range from 6 to 12 ft or more.

In 1930 Jessop stated that for 25 years the trend had been toward deeper drainage systems and that drains of 12 to 15 ft in depth were not uncommon. The high costs of very deep gravity drains justifies special effort toward pumping ground water for drainage in areas where the power costs and soil formations make pumping feasible.

198. Construction Methods and Costs In modern construction of open drains, large power-driven drag-line excavators are used as illustrated in Fig. 145. Open drains range from 5 to 15 ft or more in depth. To assure stability of the sides of the open channel in sandy soils, side slopes should not be steeper than 1½ ft horizontal to 1 ft vertical. Deep open drains, therefore, require strips of land 75 to 100 ft or

more in width, and this is one serious objection to the use of open drains in areas of high-priced lands.

A typical open drain of average depth in New Mexico is shown in Fig. 146.

Although costs of drains vary widely from time to time and from place to place, one typical example is presented. Consider an open drain 12 ft deep, having side slopes of 2 horizontal to 1 vertical, and bed width of 4 ft. The top width of channel is 52 ft, and the cross-section area is 336 sq ft; nearly 38 sq yd. The volume of excavation is 12⅔ cu yd per foot of length. At 15 cents per cubic yard the excavation cost would be $1.90 per foot. If the excavated material is left on the land near the channel the total width of waste land is approximately 100 ft, and the area per mile of drain is 12 acres. At $200 per acre the cost of land is 45 cents per foot, thus making the drain cost $2.35 per foot exclusive of bridges and culverts.

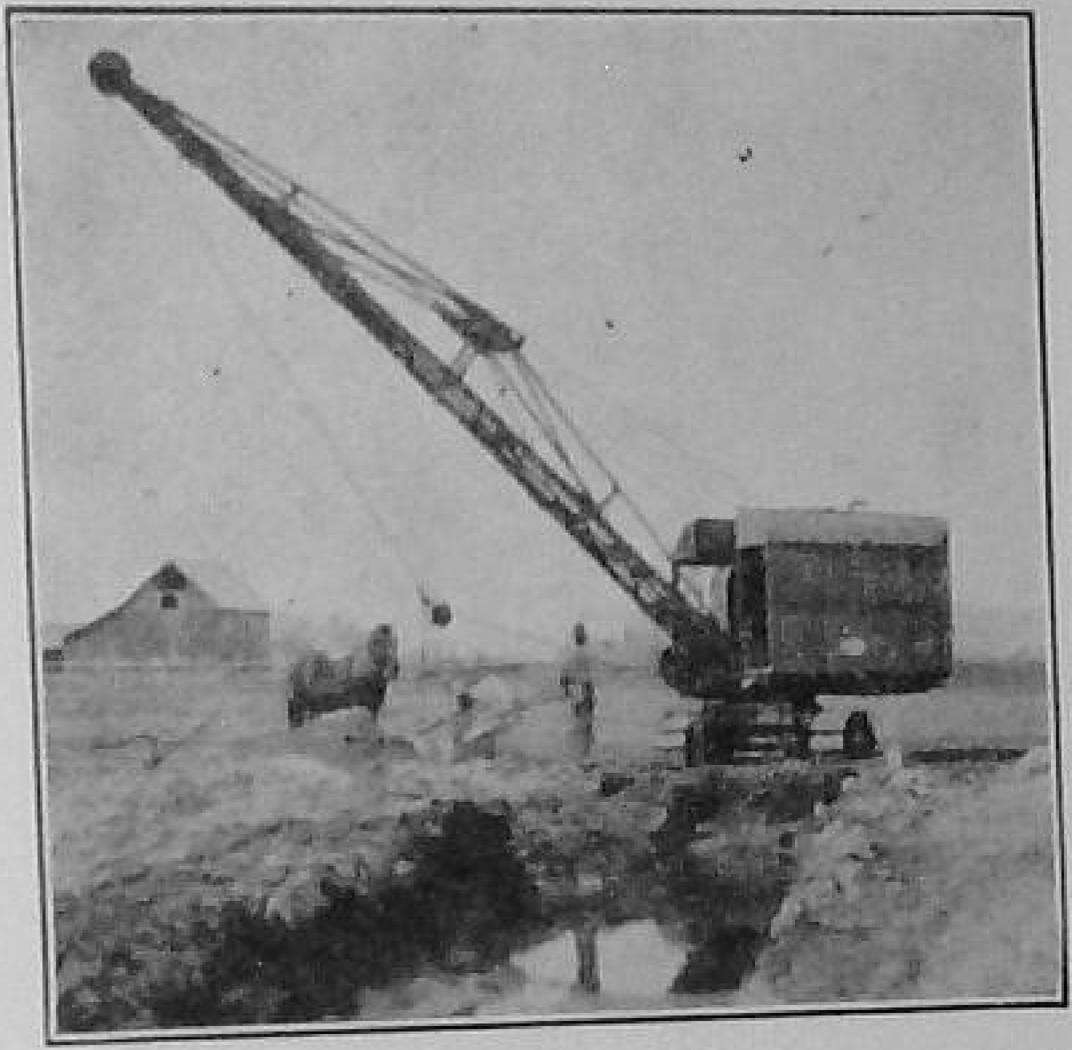


FIG. 145. Drag-line excavator in operation constructing an open drain. (Photograph by author.)

Nitroglycerine dynamite is used in the construction of open drains in some soils. When the soil is saturated and sticks of dynamite are uniform, the explosion will "propagate" from one charge to the next.

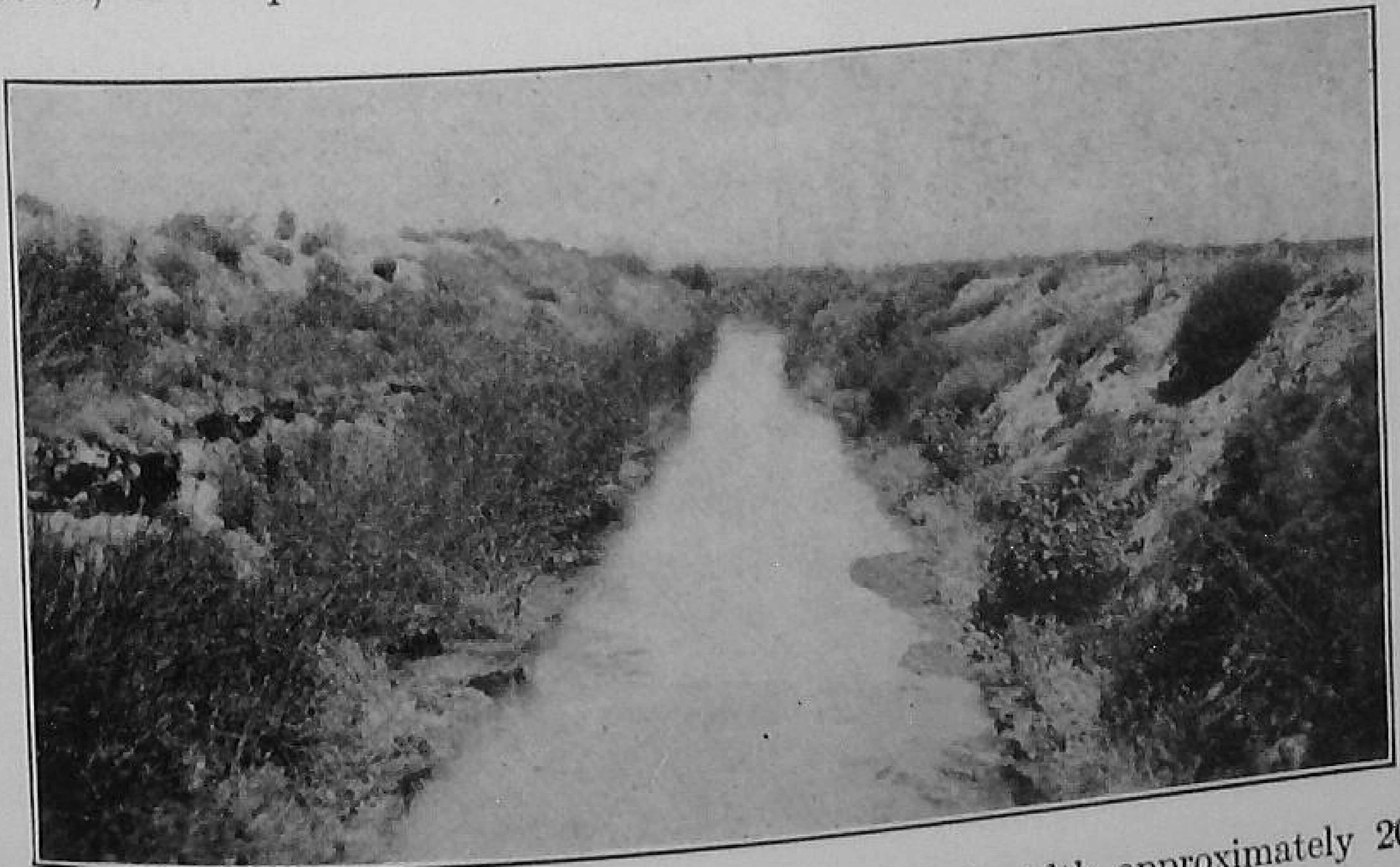


FIG. 146. Typical open drain in New Mexico, bed width approximately 20 ft, capacity 125 cfs. (Photograph by author.)

This method requires only one cap and is economical. Dynamiting affords an easy means of opening silted creeks and ditches as well as for making new open ditches. The soft bottom resulting from the blast is unsuitable for laying tile drains.

199. Tile Drainage Systems The two most common tile drainage layouts are: (1) relief drains, nearly uniform in depth and spacing, for fairly level lands, and (2) intercepting drains on irregular slopes and near sidehill lands.

FIG. 147. Concrete tongue-and-groove joint pipe ready for placing in the drainage trench. (Photograph by J. R. Barker.)

In the relief system, spacing of the drains is much influenced by the texture and permeability of the soil. In clay soils of low permeability and tile depths of 5 ft, close spacing of 200 ft may be essential to satisfactory drainage; in average loam soils, 400 to 600 ft is good spacing provided the tile is placed to depths of 6 ft or more; in sandy and gravelly soils, spacing at 800 ft or more represents the more general practice. Long main drains with short collecting laterals are called the herringbone system. The gridiron system consists of long parallel laterals connected to a short main drain. Manholes, sand traps, and observation wells at convenient points ⅛ to ¼ mile along the lines facilitate essential inspection, cleaning, and maintenance of the lines.

The depths and location of irregular cutoff drains to intercept seepage water and prevent it from flowing from sidehill lands toward the lower flat lands depend largely on the surface topography and soil formations. Intercepting drains must cut off the water flow in the sandy and gravelly soil strata because the rate of flow in these soils is very high compared with the flow in loams and clays.

200. Installation of Tile Drains During many past years trenches for closed drains were dug by hand labor. Trenching machines, like the one shown in Fig. 147, have replaced hand labor on nearly all drainage projects that are large enough to warrant moving the heavy trenching machines to and from the fields that need drainage.

Either clay or concrete drain tile is hauled, usually direct from the factory to the field, and placed along the proposed drain lines. As the trenching machine moves forward in the field, the drain pipe is laid, and each new pipe is placed against the one just laid. Some machines are equipped with hydraulic-pressure devices to press the tile firmly together. Caving of soil into the trench near the excavator is prevented by a large two-walled steel shield. Water flows from the saturated soils into the tile through the pipe

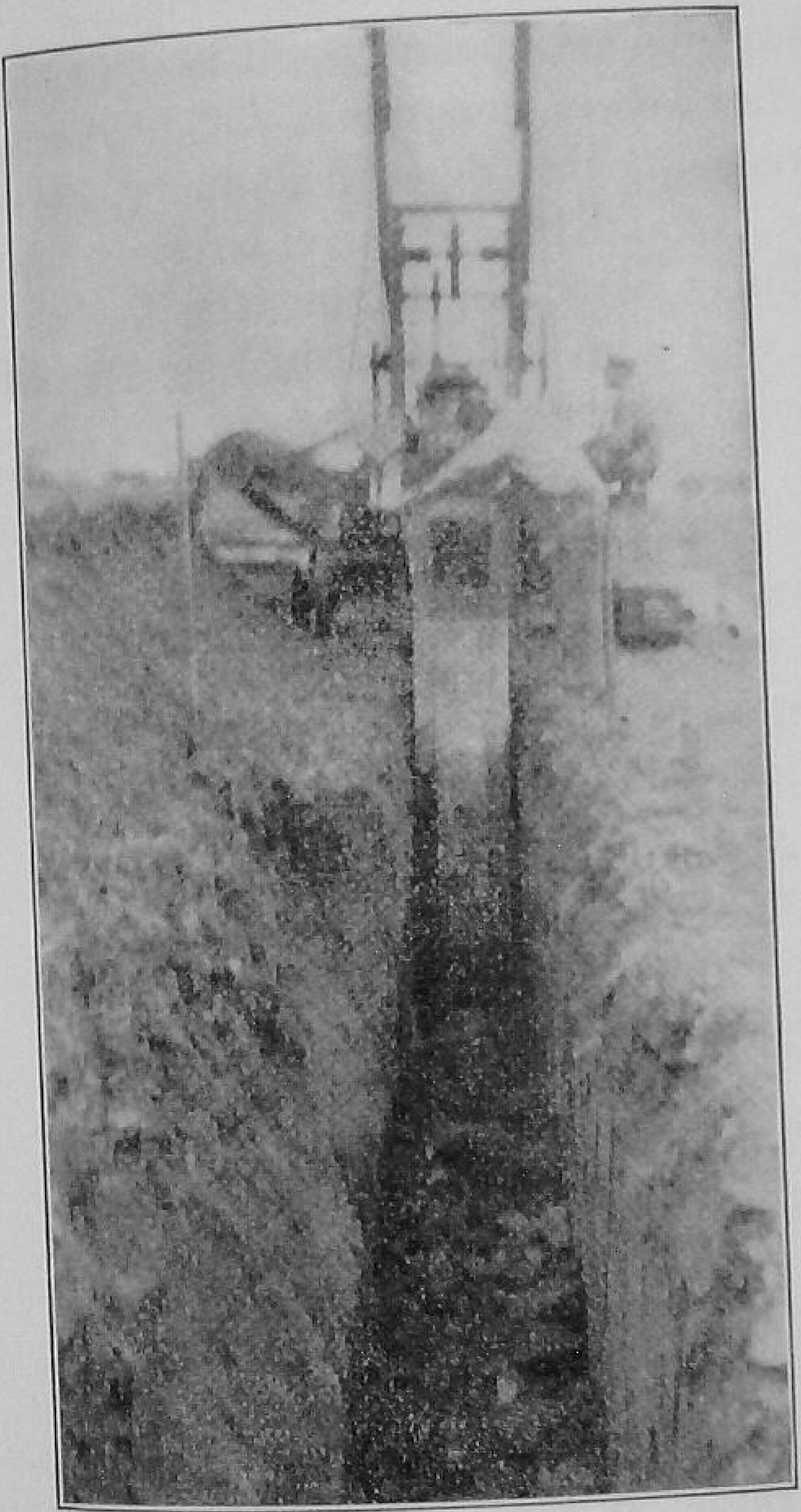


FIG. 148. Tractor-drawn excavator working in 6-ft-depth trench in sandy soil. The gravel over pipe joint can be seen near the cage. (Photograph by S. G. Margetts.)

FIG. 149. The outlet-end of a 3600-ft, 8-in.-diameter concrete pipe drain immediately after installation during wintertime in Utah. (Photograph by J. R. Barker.)

joints, not through the walls of clay or concrete pipe. To facilitate keeping soil materials from entering the tile it is good practice to place over the joints a strip of tar paper and a screened-gravel envelope about 3 in. thick and 6 in. long at each joint. The metal chute through which gravel is poured to the tile joint is shown in the lower part of Fig. 148. For soils of high stability, moderate moisture content, and no caving of banks at the time of placing the tile, the gravel may well be placed 10 to

15 ft behind the trencher. Immediately after the gravel is placed the tile should be carefully covered with soil to a depth of about 12 in. by hand labor. This process, called blinding, protects the pipe from displacement, and from damage when large volumes of earth material are forced into the trench by heavy machinery for backfilling.

The outlet end of a 3600-ft drain placed in sandy soil is shown in Fig. 149. The lower 1600 ft of the line is 8-in. concrete T & G pipe, and the upper 2000 ft is 6-in. The trenching was done in January, 1948, with the equipment shown in Figs. 147 and 148. A gravel envelope was placed around all the joints. Shortly after completing the line the drain discharge was only 36 gpm, or 1 gpm per 100 ft of line. During the irrigation season the maximum discharge was 120 gpm.

201. Maintenance of Drains The principal need in the maintenance of drainage systems is the removal of soil and vegetation from the drains.

Several types of trees and plants extend their root systems many feet to obtain water. Among these are greasewood, willows, and poplars. The roots enter the joints of closed drains and continue to grow inside the pipe, eventually obstructing the flow of drainage water. Partial obstruction by roots may retard the velocity of flow sufficiently to allow soil particles to settle in the pipe, thus gradually sealing the drain.

It is very difficult to construct drains in fine sandy soils, with joints through which the ground water may enter the pipe, and yet exclude all soil particles. The volume of soil entering the drain is small when a suitable gravel envelope is provided for the joints.

There are large variations in the quantity and velocity of water flow in closed drains. The largest flows with the greatest velocities occur during or after storms and irrigations. Soil particles entering the drains during the periods of high-velocity flow may largely be carried in suspension to the sand boxes or to the drain outlet, but as the quantity and velocity of flowing water decreases the soil particles settle to the bottom of the pipe. They may be rolled along with the low-velocity flow of water, but with a further reduction in the velocity the soils come to rest. The soil may become sufficiently stable to resist the scouring action of subsequent high-velocity flows, after which more soil accumulates, thus gradually filling the pipe unless the soil is removed.

The term "wash-ins," popular among the farmers in some of the drainage districts, refers to holes formed in the land where irrigation water flows downward through the backfilled trench, washing large

volumes of soil into the closed drain through the joints. Wash-ins have occurred most frequently during the periods soon after construction, and less frequently as the backfill material settled in the trench, thus becoming more compact.

Wash-ins have been attributed to careless irrigation methods. Irrigation water applied excessively and allowed to pond over the drains is especially conducive to wash-ins. The damage caused by wash-ins is

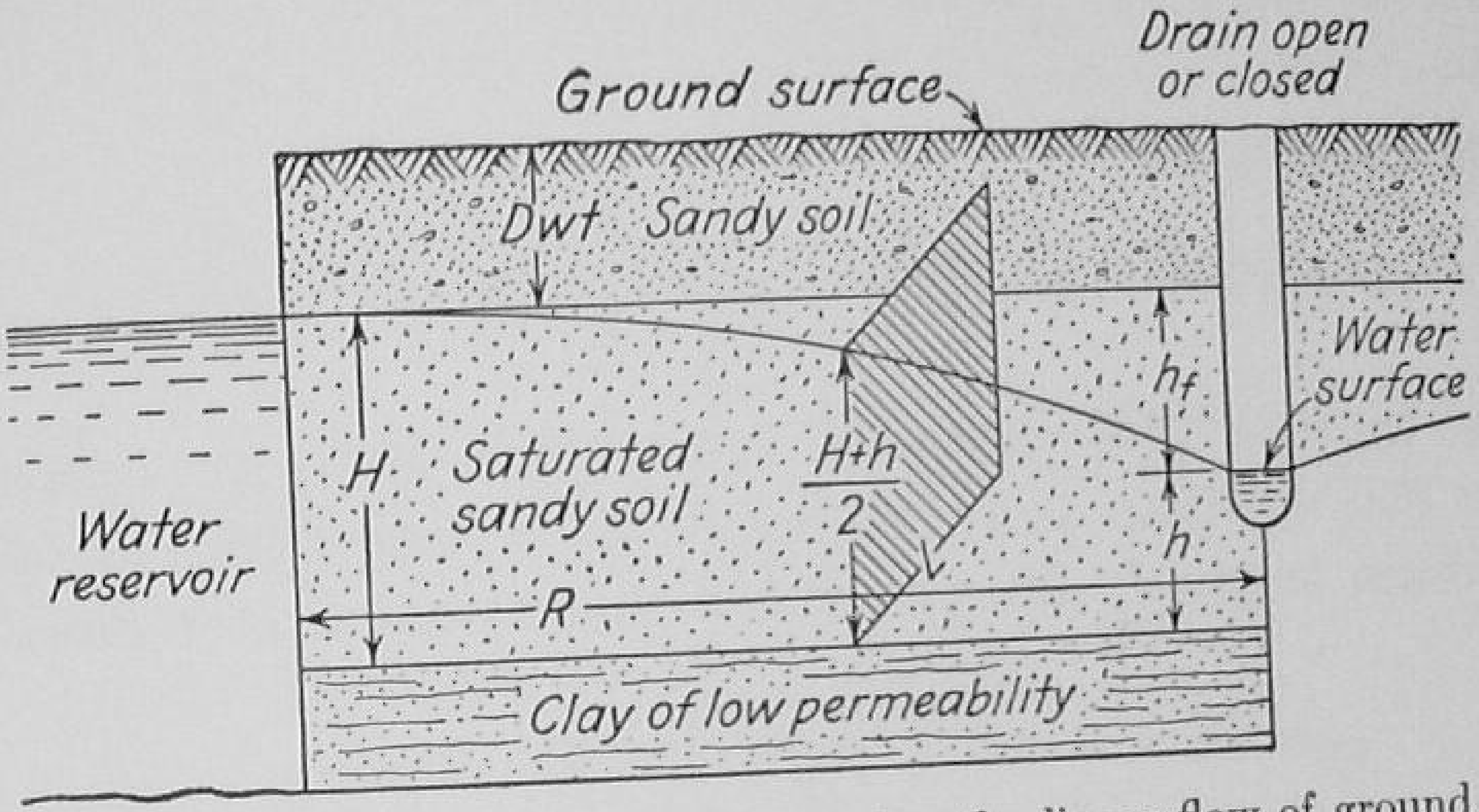


FIG. 150. Illustrating for sandy soils over clay the linear flow of ground water toward drains spaced $2R$ ft in which the water table midway between drains is $H - h$ ft above the water surface in the drain.

twofold: the soil washed in obstructs the drains, and the holes formed in the land surface render that part of the land unproductive until repaired.

In sandy soils drain pipes have been found shifted as much as 90° from alignment. Loosely placed or unmatched joints cause this condition. Drainage water flowing over a wide or unmatched joint erodes the soil from under the joint, thus allowing it to settle. As the joint settles and the pipe ends separate the eddies in the hole forming under the joint become greater, thus increasing the eroding effect of the water. This continues until the flow of water in the drain is completely blocked by the soil closing in on the joint or by silting in the lower reaches of the drain.

202. Drain Depths, Spacing, and Ground-Water Flow Two types of soil profile are considered to illustrate the influence of drain depth, spacing, and other factors on the quantity of flow of ground water toward and into the drains.

In highly permeable sandy soils, underlain by compact clay of low permeability 6 to 10 ft below the land surface, as illustrated in Fig. 150, the ground-water flow is essentially *horizontal* toward the drains.

To simplify the illustration, the source of water flowing toward the

drain is considered a reservoir as illustrated on the left of Fig. 150. The water surface is maintained in the reservoir and adjoining soil a distance of H ft above the clay. Flow from the reservoir to the drain is steady, it being assumed for simplicity that the reservoir is the only source of water.

Ground water actually flows to the drain from both sides. Let $2q$ represent the flow into a drain in length L. Then the ground-water flow from one side to the drain is

$$q = av$$

and from Darcy's law,

$$v = k\frac{h_f}{R} = k\left(\frac{H - h}{R}\right)$$

Consider the depth of saturated sand about midway between the reservoir and the drain as average; then the average area of saturated soil, in drain length L, through which the ground water flows is:

$$a = \left(\frac{H + h}{2}\right) \times L$$

and the quantity of flow from the reservoir to the drain

$$q = \left(\frac{H + h}{2}\right) L \times k\left(\frac{H - h}{R}\right)$$

$$= \frac{kL(H^2 - h^2)}{2R} \tag{48a}$$

The quantity of flow to the drain from reservoirs on both sides would be

$$Q = 2q = \frac{kL(H^2 - h^2)}{R} \tag{48b}$$

from which

$$R = \frac{kL(H^2 - h^2)}{Q} \tag{48c}$$

For example, assuming that the reservoir is the only source of ground-water flow in a 15-ft depth of waterlogged sand, what spacing of drains will draw, from the soil on both sides of a drain, a stream Q of 1 cfs in 2500-ft-length of a 15-ft-depth drain in which the water is 2 ft deep, when the water table is 5 ft below ground midway between the drains?

Referring to Fig. 150, for this example:

$$H = 10 \text{ ft} \qquad L = 2500 \text{ ft}$$
$$h = 2 \text{ ft} \qquad q = 1 \text{ cfs}$$

The average permeability measured in field soils in this case is

$$k = 2 \times 10^{-3} \text{ ft/sec}$$

Then since the drain spacing S equals $2R$ it follows that

$$S = \frac{2 \times 2 \times 2500 \times (100 - 4)}{1000 \times 1} = 960 \text{ ft}$$

The lengths H, h, and L can be accurately measured at any time, and q can be measured within 5 percent accuracy. However, computa-

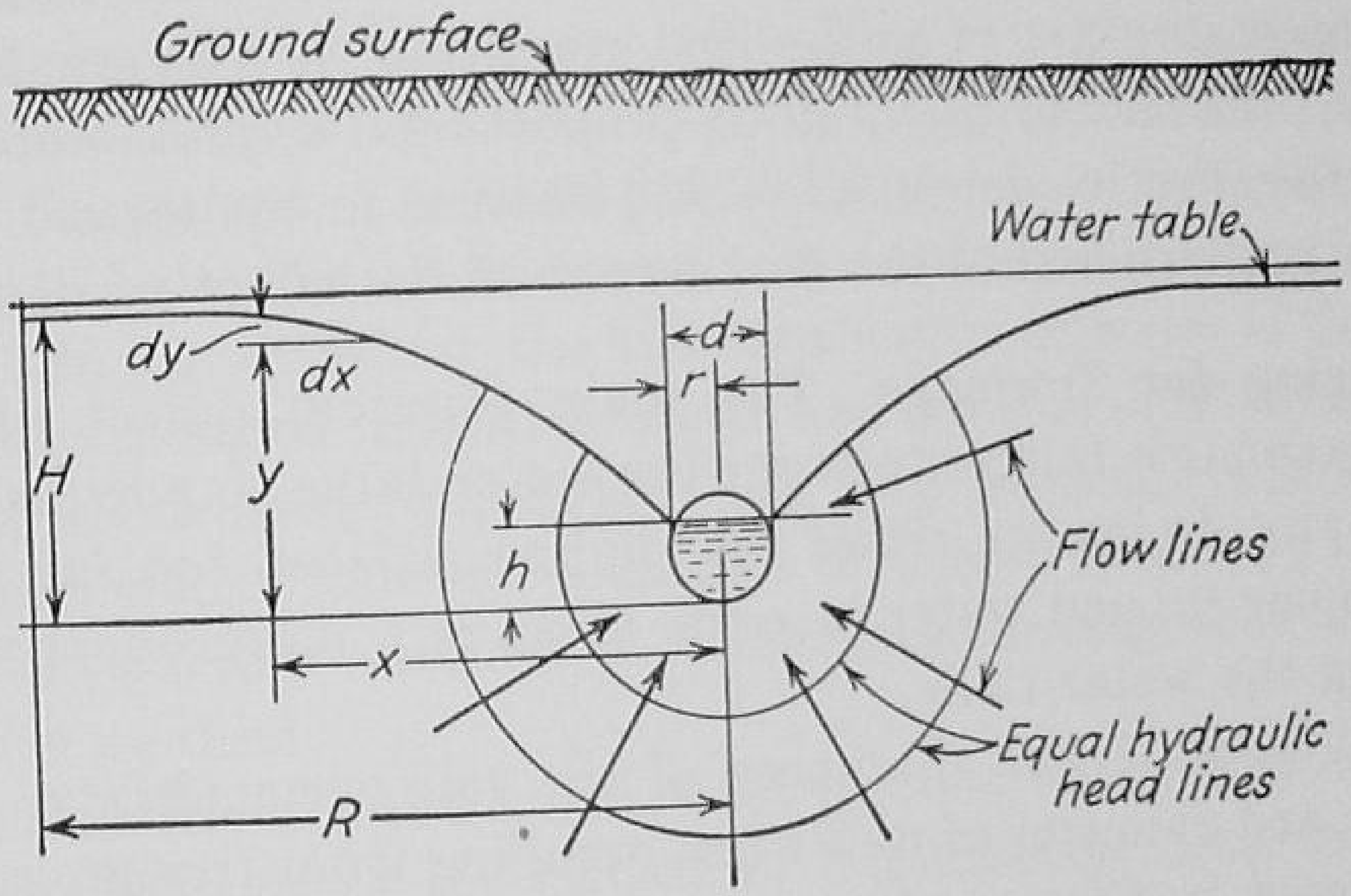


FIG. 151. Illustrating for deep, uniform soils the radial flow of ground water toward drains spaced $2R$ ft, in which the water table midway between drains is $(H - h)$ ft above the water surface in the drain.

tions of drain spacing using equation 48c must be regarded as *only approximations* because of the fact that permeability k varies greatly in field soils.

In saturated sandy field soils having clay subsoils the flow toward the drain is a maximum near the drain, and it decreases as distance from the drain increases. It is assumed that there is no flow through the vertical plane midway between the drains, and on each side of this plane the flow is in opposite directions. For these field conditions in which the source of drainage water is assumed to be downward flow from unsaturated irrigated soils to the water table, Donnan has derived an equation comparable to equation 48a, the difference being that the quantity of flow is twice that shown by this equation for the same soil permeability, differences in water surface elevations, and spacing of drains.

For soils of great depth and approximately uniform permeability, as illustrated in Fig. 151, the ground water flows radially toward the

drain from all directions. With these soil conditions and designating radial flow *through a semicircular area* (a little less than the actual area) it is essential to use the calculus to derive the rational equation

$$Q = \frac{\pi k L(H - h)}{2.3 \log_{10} R/r} = \frac{\pi k L(H - h)}{2.3 \log_{10} S/d} \tag{49}$$

in which all the symbols but S and d have the same meaning as in equation 48b. S is the space between drains, and d is the diameter of the drain.

The basic differences of the two soil-and-water-flow conditions of special importance are: For the first condition, if h is small as compared to H, the flow to the drain is proportional *approximately to the square* of the effective depth $(H - h)$, whereas in the second condition the flow is proportional to the *first* power of the effective depth.

203. Pumping for Drainage The main physical defect of gravity drainage systems is failure to lower the water table to adequate depth. Many gravity drains are either too shallow, spaced too far apart, or both. Pumping ground water in some areas is a more effective means of lowering the water table.

The influences on well discharge of the soil permeability, effective well depth, and diameter of well when pumping from free ground water are considered in Chapter 5, Article 70. In pumping from confined ground water in artesian aquifer of depth D the water flows radially to the well through cylindrical surfaces having a vertical axis and the following well-discharge formula applies:

$$Q = \frac{2\pi k D(H - h)}{2.3 \log_{10} R/r} \tag{50}$$

Comparisons of equations 49 and 50 show that if the length of drain L in equation 49 is equal to the depth of aquifer D in equation 50, and all other items are the same, then the flow to the well through *vertical cylindrical* surfaces would be twice that to the drain through *horizontal semicylindrical* surfaces.

Pumping ground water for drainage is influenced favorably by adequate depths and permeabilities of the water-bearing formations, by high values of pumped water for irrigation, and by low power costs. The experiences of one California irrigation district and of the Salt River Valley Water Users Association in Arizona indicate the feasibility of ground-water pumping where subsoils are favorable and the pumped water can be used for irrigation.

From 1907 to 1922, the Modesto Irrigation District in California

spent $356,000 for construction and maintenance of gravity drains for 45,000 acres. Sub-irrigation had prevailed for several years, and in many locations where the rich soil had previously produced abundant crops yields decreased, orchard trees died, and vines withered, for the alkali salts had become sufficiently concentrated to render the soil unfit for plant growth. In 1922, the Modesto group drilled the first drainage well, and by 1939 had put into operation 77 pump wells, reaching a combined capacity of 207 cfs. On 50,000 acres subject to Modesto's high water table in a 17-yr period the drainage-pump cost per acre was $12.24, counting $4.38 for construction, maintenance, and operation, and $7.86 for power cost. This is a third more than the per-acre cost for gravity drains. During the period in which the district operated the pumps, a total of 602,000 acre-feet of water was pumped and about 75 percent of that water was utilized for irrigation. At the rate of $1.36 per acre-foot, the 1940 evaluation of water in the Modesto district, the pumped irrigation water had a value of $612,050, entirely offsetting all drainage-pumping costs. The Modesto experience leads to the conclusion that the operation of deep-well pumps is not only a most satisfactory method of subsurface drainage but also a self-liquidating method.

In the Salt River Valley, Arizona, irrigation was greatly advanced in 1911 by completion of the Bureau of Reclamation Roosevelt dam and reservoir. Drainage did not become a problem there until about 1918; then the Water Users Association decided to pump ground water. The association pumped 50,000 acre-feet in 1920 and the same amount in 1921. In 1922, it increased the drain to 100,000 acre-feet, and the menacing water table began to go down. Since then, the volumes of water pumped annually have increased, and the water-table depth has also greatly increased, thus solving the drainage problem. In 1946, the association operated 200 pumped wells, drawing 400,000 acre-feet of water, nearly one-third of its irrigation water supply, and the average depth of the water table was greater than 50 ft.

204. Drainage Enterprises Group action is essential in the drainage of irrigated land. For one landowner to be able to provide adequate drainage for his land without cooperating with his neighbors is the exception rather than the rule. Group action in some areas is obtained by organizing drainage districts which are quasi-public corporations provided for by state laws and which have authority to tax irrigated land for drainage purposes.

Two principal purposes influence the organization of drainage districts, namely: (1) to consolidate into one drainage agency the lands

of an area in need of drainage and contributing to that need, and (2) to provide the authority and the procedure, and to assign the responsibility for the design, financing, construction, and maintenance of drainage systems.

Noteworthy powers of a drainage district are: (1) the power to include in the district all lands to be benefited by the drainage system, and thus assure strength of the district and ability to promote equity in

TABLE 38

DRAINAGE AREAS IN THE 11 WESTERN STATES AS REPORTED IN THE 1940 CENSUS, TOGETHER WITH LENGTHS OF OPEN AND TILE DRAINS

State	In Drainage Enterprises, thousands of acres	Adequately Drained, thousands of acres	Poorly Drained, thousands of acres	Open Drains Completed, miles	Tile Drains Completed, miles
Arizona	299	297	0.3	101	9
California	2667	2270	135	6091	326
Colorado	468	444	10	973	365
Idaho	659	605	19	968	175
Montana	373	352	17	421	74
Nevada	153	134	..	426	...
New Mexico	306	284	12	625	309
Oregon	349	299	29	780	151
Utah	202	123	41	268	1619
Washington	406	368	6	885	179
Wyoming	313	288	13	643	262
Totals	6195	5464	282.3	12,181	3469

its dealings with landowners; (2) the power to tax lands of the district and enforce tax collections. The second power carries the authority to foreclose on tax-delinquent land and sell it if necessary.

Drainage districts have legal authority to carry out all the functions and activities pertaining to drainage of farm land including financing, design, and installation of drains, and their operation and maintenance.

There must be a need for drainage in the area proposed for the district, and it must be shown that the benefits to the included lands will exceed the costs; the desires of a majority of the landowners to participate must be expressed; the specified organizing procedure must be carried out. Land ownership within a drainage district is the usual requirement for membership and participation in district activities.

After a district has been organized, its taxing procedure set in operation, its capital financing provided, and its drainage system installed, its problems concern largely management, operation, and maintenance, and the discharging of financial obligations.

In Utah a board of three supervisors constitutes the governing body of the drainage district and carries the responsibility for all the district affairs. Supervisors are appointed by the county commissioners, usually upon nomination by the district landowners. The supervisors elect from their number a president, secretary, and treasurer. They must ascertain the needs for drainage in the area and determine the nature, extent, and probable cost of a drainage system designed to meet those needs. It is also their responsibility to provide capital financing for the installation of the drainage system, usually involving the issue and sale of district bonds, and to set up an equitable taxing system to provide adequate and dependable finances to meet the annual revenue requirements. The ability and willingness of supervisors to serve the district may determine the success or failure of the enterprise.

The larger irrigation enterprises, notably in Arizona and California, including irrigation districts, and mutual water users' associations are developing more and more interest in the drainage of irrigated lands. Mutual irrigation companies of Utah have done very little drainage work, but the trend is toward combining responsibilities for irrigation and drainage systems into one organization particularly where state legal authority is adequate for an irrigation company to assume responsibility of irrigation and drainage.

13
Time of Irrigation

Two major considerations influence the time of irrigation, namely, (*a*) the water needs of the crops, and (*b*) the availability of water with which to irrigate. The water needs of the crop are of paramount importance in determining the time of irrigation during the crop-growing season on irrigation projects which obtain their water supplies from storage reservoirs or from other dependable sources of water. Some irrigated areas have a deficient water supply during the irrigation season but an abundance of water during the late autumn or winter and early spring. Irrigation farmers cannot always apply water when the crop is most in need; sometimes to save the water they must apply it even though the crop does not need it. Both crop needs and available water supply must be considered in a discussion of the proper time to irrigate.

205. Crop Needs Growing crops use water continuously, but the rate of use varies with the kind of crop grown, age of the crop, the temperature, and the atmospheric conditions—all variable factors. It is essential, in irrigation farming, to use the root-zone soils as storage reservoirs for available water. At each irrigation a volume of water sufficient to supply the needs of the crop for a period varying from a few days to several weeks is stored in the unsaturated soil in the form of available soil water. How frequently the water should be applied to soils of different properties in order to best supply the crop needs is a question of real practical significance. The factor of major importance in arriving at the desirable frequency and time of irrigation is the water need of the crop.

206. Limiting Soil Moisture Conditions The growth of most of the crops produced under irrigation farming is stimulated by moderate quantities of soil moisture and retarded by excessive or deficient amounts. A certain quantity of air in the soil is essential to satisfactory crop growth; hence, excessive flooding and filling the soil pore spaces

with water, thus driving out the air, inhibits proper functioning of the plants even though it supplies an abundance of available water. On the other hand, soils having deficient amounts of water hold it so tenaciously that plants must expend extra energy to obtain it; and slight further decrease in the water supply decreases the moisture content until the rate of absorption is not high enough to maintain turgidity, and permanent wilting follows. At some soil moisture content between these two extreme moisture conditions it has been thought that plants grow most rapidly, and this has been designated the *optimum* moisture percentage.

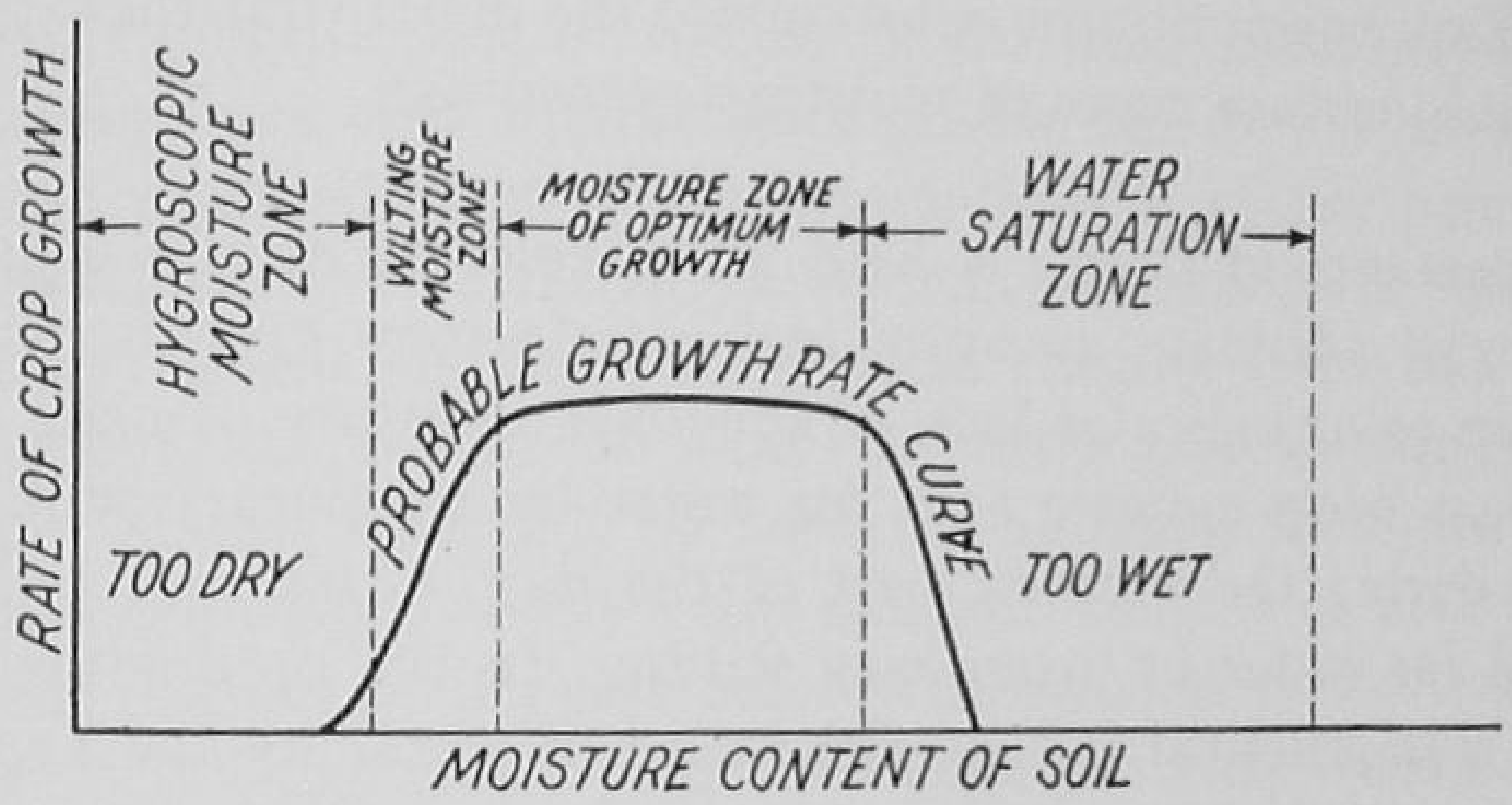


FIG. 152. Illustrating the probable growth rate of crops as influenced by different amounts of moisture in the soil.

Extending knowledge of these two limiting soil moisture conditions, i.e., the permanent wilting percentage and the optimum percentage, has been the objective of considerable research. Because of the wide variations in the physical properties of different soils it is easy to understand that the moisture percentage in a clay soil at permanent wilting of a plant may be several times the moisture percentage in a sandy soil when the same plant wilts permanently. Questions that are not so easily understood are these: In a particular soil do all plants wilt at about the same moisture percentage? Is there a critical moisture percentage (or narrow zone of moisture content) at which potatoes, beets, alfalfa, grains, and all other standard crops wilt in spite of variations in sunshine, wind, atmospheric humidity, and so on? Extended investigations by Briggs and Shantz led to the conclusion that nearly all plants wilt at substantially the same moisture percentage in a particular soil.

Of equal interest and importance is the so-called optimum moisture percentage. As the moisture percentages increase above the wilting point (or zone) does the growth rate of crops increase appreciably until the optimum is reached and then decrease until the field capillary-

water capacity is reached? Or, is the growth rate substantially the same within a wide range of moisture content from a point slightly above wilting to the field capillary-water capacity?

The probable influence of variation in moisture percentage on the rate of growth of plants, based on the results of research, is illustrated in Fig. 152. The heavy line curve represents roughly the change in rate of growth of crops as the moisture percentage of the soil increases from the wilting content to the saturation content. It has been thought that the maximum growth rate of plants occurs at rather definite moisture percentages. Investigations by the California Agricultural Experiment Station substantiate the belief that these processes occur within certain zones of moisture percentage.

207. Appearance of Crop A light green color in alfalfa is generally indicative of adequate moisture and satisfactory growth, whereas a dark green color indicates lack of adequate moisture. Among the root crops, sugar beets indicate need for water by temporary wilting, particularly during the warmest part of the day. Grain crops also indicate need for water by temporary wilting. In the production of fruit crops, it is impractical to detect the need of water by the appearance of the leaves of the trees. Serious retardation in growth rate sometimes occurs before the leaves indicate clearly a need for water. It is therefore more essential to base the time of irrigation of orchards on observations of the moisture content of the soil. The use of any crop as an indicator of the need for irrigation water is open to the same objection that applies to its utilization in fruit production. Crop growth should not be retarded by lack of available soil moisture; and the practice of withholding irrigation until the crop definitely shows a need for water is very likely to retard the growth of the crop.

208. Available Water in Soil It is essential to maintain readily available water in the soil as long as it is desired to have crops make satisfactory growth. The water held by a soil after permanent wilting of plants is designated unavailable water. In coarse-textured soils the unavailable water is quite low, from 1 to 3 percent of the weight of dry soil, whereas in a very fine-textured soil it is sometimes as high as 20 percent. The wide variations in the amount of unavailable water to a particular plant in different kinds of soil make the slight variations due to the different capacities of plants to absorb water quite insignificant. The variations in unavailable water percentages are of major importance in using the soil moisture content as an index of when to irrigate.

209. Wilting Moisture Percentage The moisture percentage held by the soil after permanent wilting of plants is known as the wilting point, or the wilting coefficient. Briggs and Shantz found a fairly definite relation between the moisture equivalent of all soils and the wilting coefficient. More recent investigations by Veihmeyer and Hendrickson indicate rather wide departures from the Briggs and Shantz finding that the wilting coefficient is equal to the ratio of the moisture equivalent to the number 1.84. In order to make effective use of the moisture content of a soil as guide to proper time to irrigate it is clearly essential to know approximately the wilting point of the soil considered. Computations of wilting points from moisture-equivalent determinations are only approximate guides and should be used with caution and replaced by direct determinations of wilting points where possible. Veihmeyer and Hendrickson found variations in the ratio of moisture equivalent to the wilting point ranging from 1.73 to 3.82. They reached the conclusion that the ratio 1.84 recommended by Briggs and Shantz may not be used for all soils, "because it seems that plants are able to reduce the moisture content of different soils to different degrees of dryness before the stage of permanent wilting is reached." Wilting under *field conditions* probably occurs within a certain restricted zone or range of moisture content rather than at a precise moisture percentage. Knowledge of what is the upper limit of the wilting zone for a particular soil is of practical importance. Hendrickson and Veihmeyer state that plants do obtain some water from the soil below the permanent wilting percentage but that the rate at which they can obtain it is not high enough to enable the plant to remain turgid. The water below the permanent wilting percentage is not readily available.

210. Growth Rate for Moisture Above Wilting Zone Studies of soil moisture and plant relations seem to warrant the conclusion that the growth rate of plants is not reduced by lack of available water so long as the soil moisture content is above the wilting zone.

The field experimental work of Hendrickson and Veihmeyer with peaches in San Joaquin Valley, California, led them to conclude that the "permanent wilting percentage is a critical soil moisture content," and "that trees either *have* readily available moisture or *have not.*"

Studies by Shull concerning the variation of the tension by which water is held by the soil as the moisture content varies support the conclusions reached by Hendrickson and Veihmeyer. Shull found that, at moisture contents above the wilting point, a large change in water content causes but a slight change in the tension. At moisture contents

below the wilting point, however, a slight change in the moisture content very greatly changes the tension with which the water is held. Shull's findings are confirmed by the work of Thomas on aqueous vapor pressure of soils. In a study of plant and soil relations at and below the wilting percentage Magistad and Breazeale confirm the results of the work by Shull and Thomas. Figure 153 shows relatively little decrease in suction force as the moisture content increases from the wilting point, about 19 percent, to the moisture equivalent, about

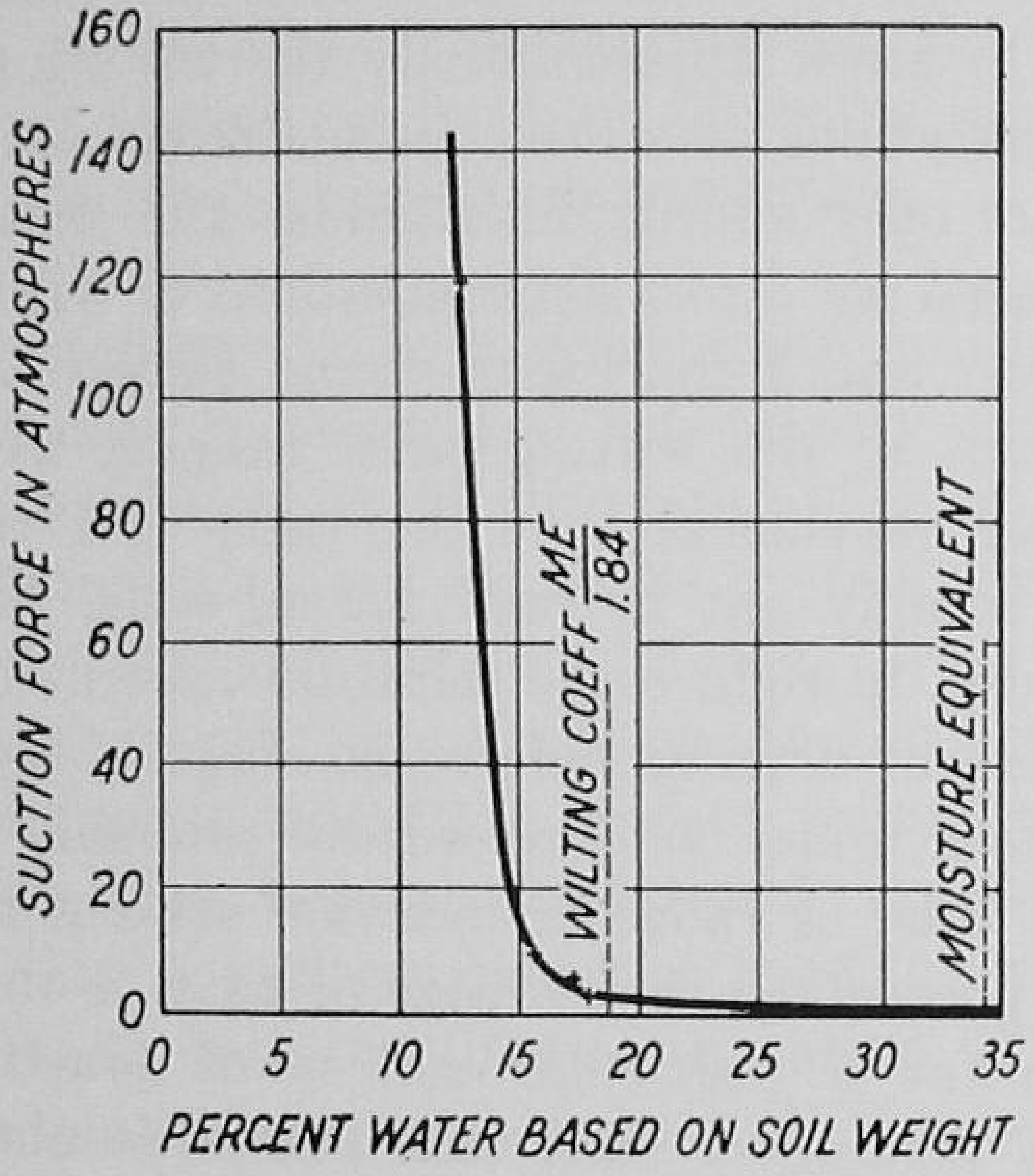


FIG. 153. Suction force or tension with which water is held in a silty clay loam with varying moisture percentages. (*Ariz. Agr. Exp. Sta. Tech. Bul.* 25.)

34 percent. It therefore seems reasonable to believe that the growth rate of crops, so far as it may be influenced by moisture content of the soil, would not change appreciably as the moisture content increases from the wilting point up to the moisture equivalent which, in some fine-textured soils, represents approximately the field water capacity.

211. Moisture Needs of Different Soils On the sandy loam of the New Mexico Station farm it was found that plants do not suffer when the average moisture content of the upper 6 ft of soil falls to 7 percent. The changes in moisture content during a period of 10 days after irrigation in the first, third, and fifth foot sections are presented in Fig. 154. The plot produced alfalfa and was cultivated. The plot was given 3-in. irrigations; the average seasonal depth during the years in which moisture determinations were made was 42 in. The maximum changes of moisture content were in the surface foot, and the moisture

content in the third and fifth foot sections continued to rise for several days after irrigation. The moisture content in the cultivated plot, first and third foot sections remained well above the 7 percent minimum during the period of observation.

Powers found it best to irrigate potatoes when the moisture content of a heavy gray silt loam of western Oregon dropped to 20 percent.

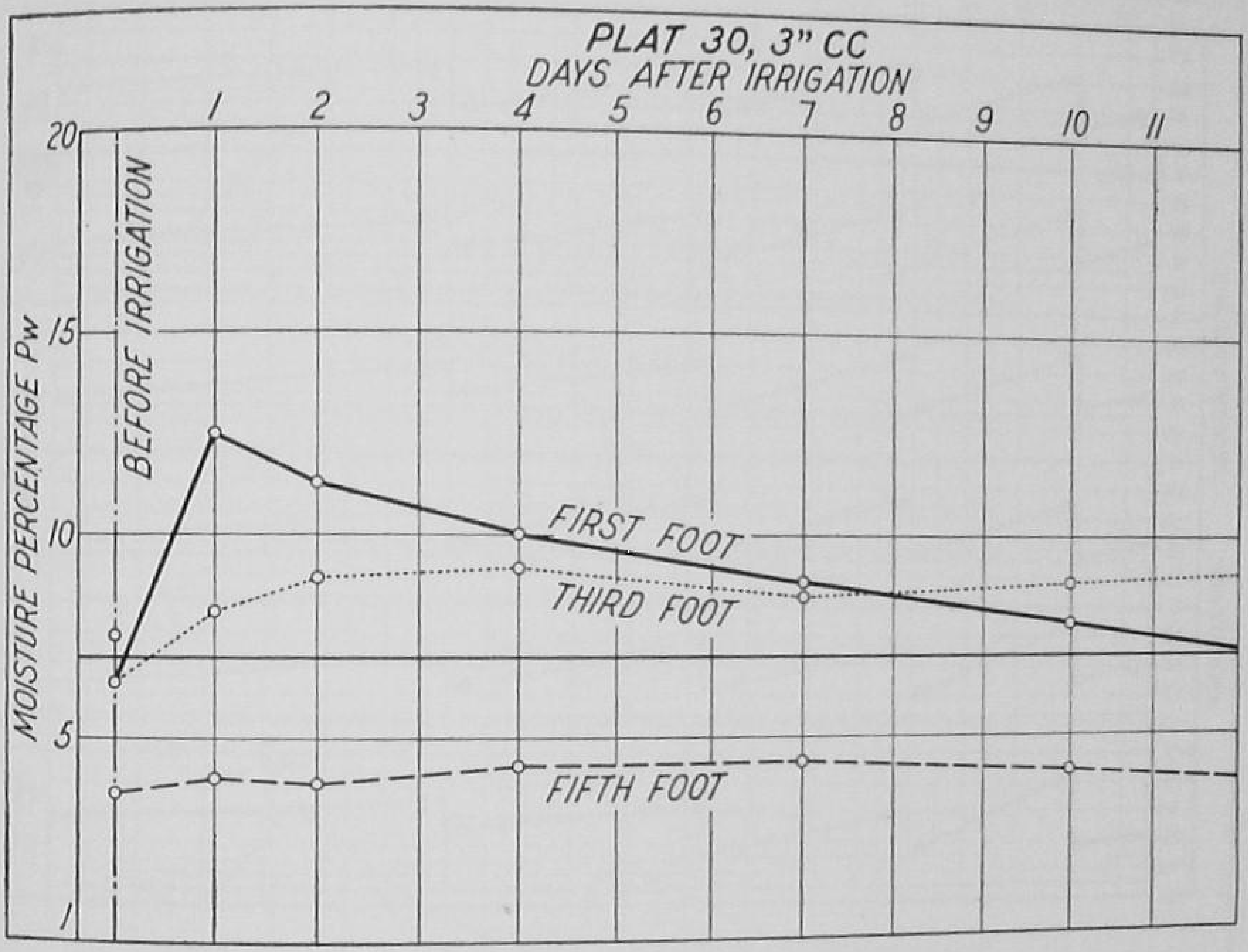


FIG. 154. Showing increase in moisture percentages due to irrigation on cultivated alfalfa plot and decreases during the first 10 days after irrigation. (From data in *New Mexico Agr. Exp. Sta. Bul.* 123.)

A moisture percentage of 12 to 13 indicates that irrigation of the deep loam soils of the Utah Experiment Station is desirable. Moisture-equivalent percentages are not reported for the New Mexico and Oregon soils. The moisture equivalent of the Utah soil is 22 percent, from which the computed wilting coefficient is 12 percent.

Adams and others found that alfalfa grown under favorable conditions in the Sacramento Valley, California, produced nearly 7 tons per acre even though the moisture percentage dropped to the wilting point in the surface foot of soil before each irrigation of the season. The moisture percentage in each foot section of soil is shown in Fig. 155 at 10 different periods during the crop-growing season.

Investigations by Hendrickson and Veihmeyer indicate that although there is a "remarkable constancy of the residual moisture content for

a given soil when permanent wilting is attained, a common factor to evaluate the amount of water which remains in soils at permanent wilting cannot be used."

The seasonal moisture percentage variations of the soils of different

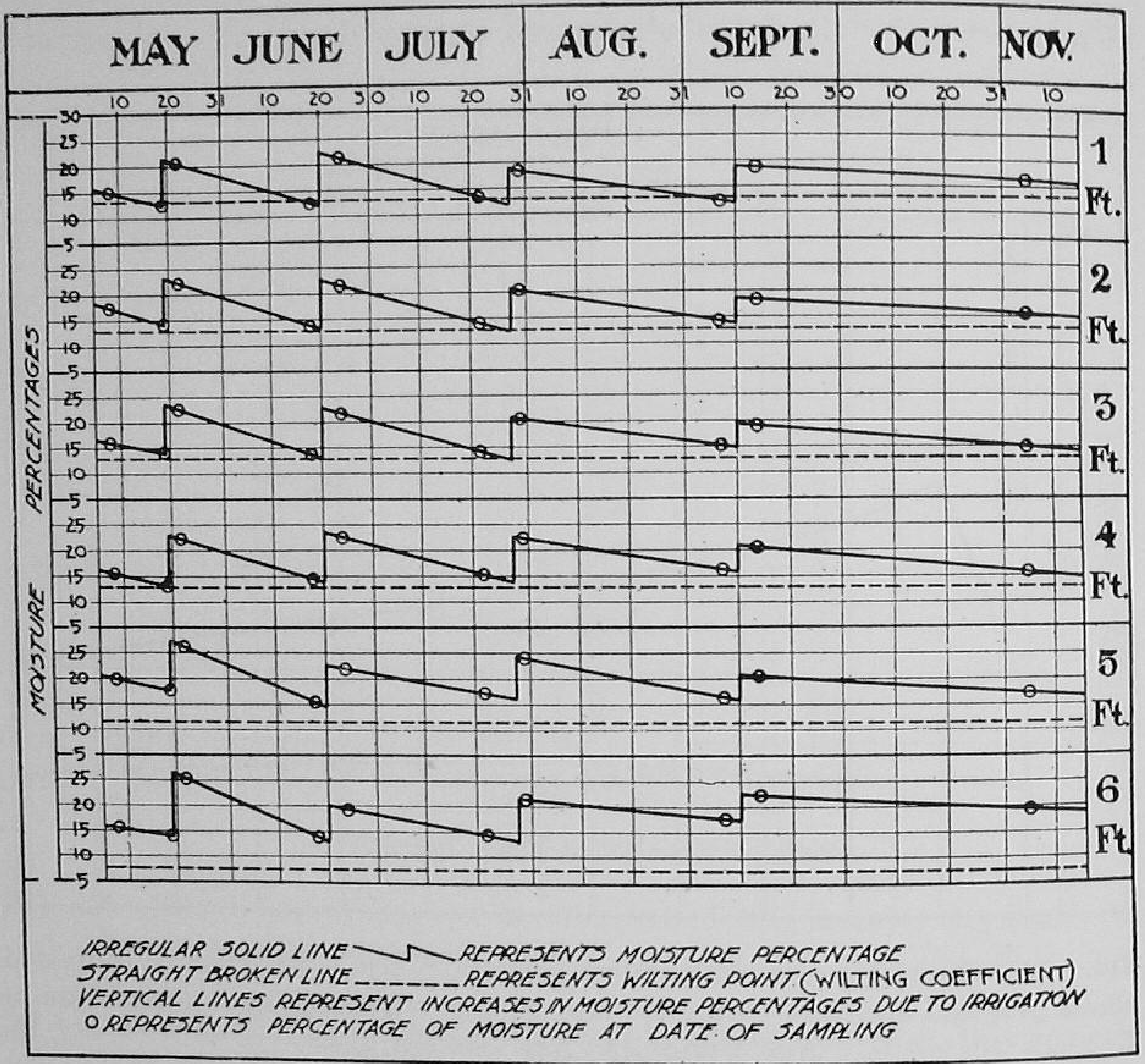


FIG. 155. Showing seasonal variation in soil moisture percentages. Wigno alfalfa field, Los Molinos, 1914. (*Calif. State Dept. of Eng. Bul.* 3.)

experimental plats at Delhi, California, under various irrigation treatments are presented in Fig. 156.

The average depths of water applied in each of the four treatments, or groups of treatments, were as follows:

Treatments *A* and *F* received the greatest depths of water, an average of 25.3 acre-inches per acre during each year; treatment *D* received the next largest, an average annual application of 19.8 acre-inches per acre; and treatment *B* received less water than *D*, or 13.4 acre-inches per acre; and treatments *C*, *G*, and *E* received only approximately one-half the depths applied on *A* and *F*, or 11.1 acre-inches per acre each year.

The soil of the Delhi experimental farm is classified as an Oakley fine-sand. The student should note the low moisture content of the upper 3 ft of soil at permanent wilting represented in Fig. 156 by the heavy horizontal line and the high average seasonal moisture content

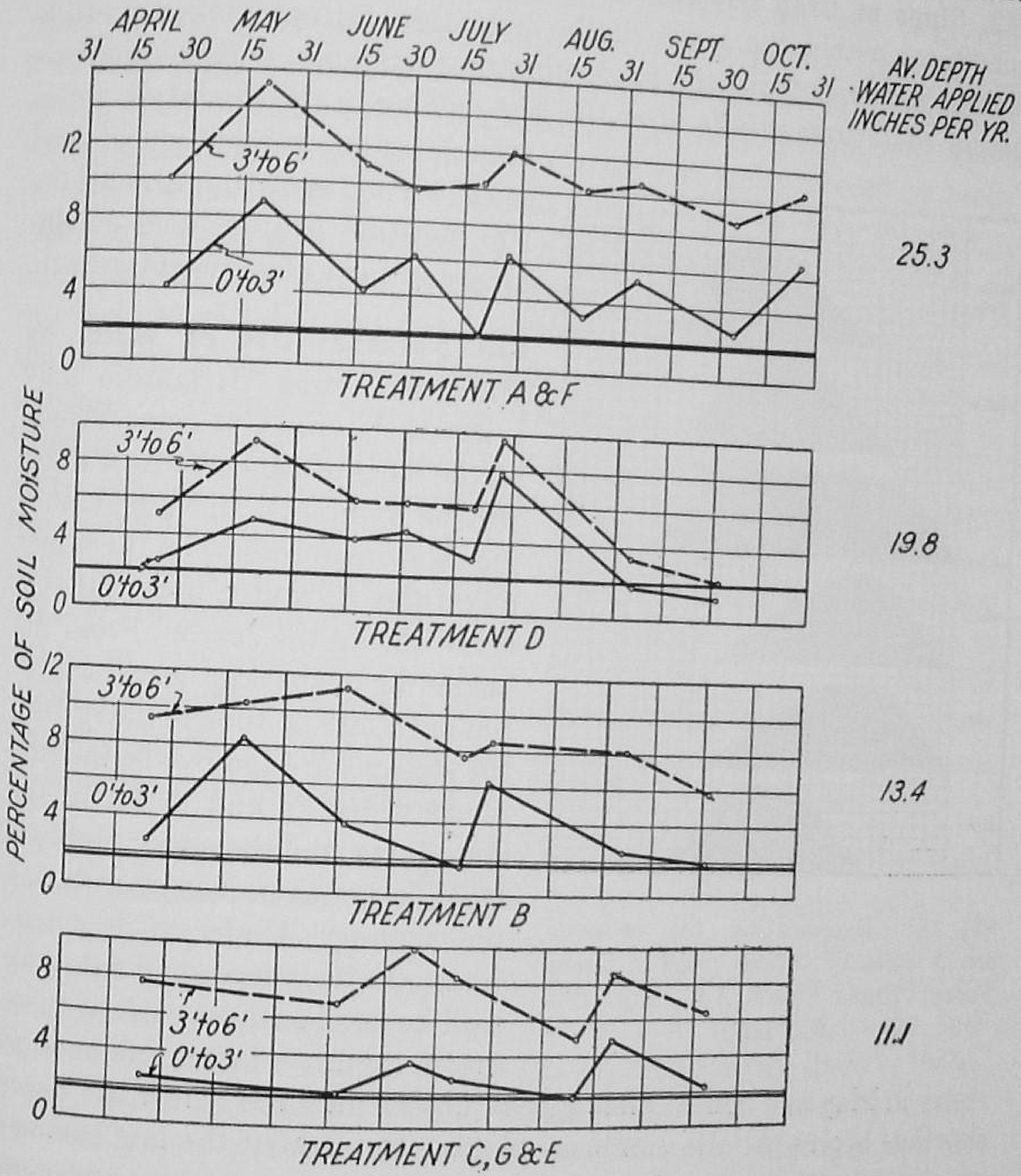


FIG. 156. Moisture contents of soil in orchard treatments at Delhi, 1924. The permanent wilting percentage of the 0 to 3-ft depth is indicated by the heavy horizontal lines. (*Calif. Agr. Exp. Sta. Bul.* 479.)

maintained by the larger applications of irrigation water. The wide range in variation of moisture content at the time irrigation water is needed to supply available moisture, as reported above, stresses the influence of soils in their different capacities to withhold water from plants. It is important to know the permanent wilting percentage of

each soil in order to use the moisture content as an index of the time when irrigation water should be applied to maintain readily available water in the soil.

212. Stage of Crop Growth The degree of control of soil moisture conditions within the reach of the irrigation farmer makes possible special attainments in crop production. For example, withholding irrigation water from alfalfa after the first cutting in the mountain states stimulates the production of seed in the second growth, provided the soil moisture content does not increase so far as to prevent growth.

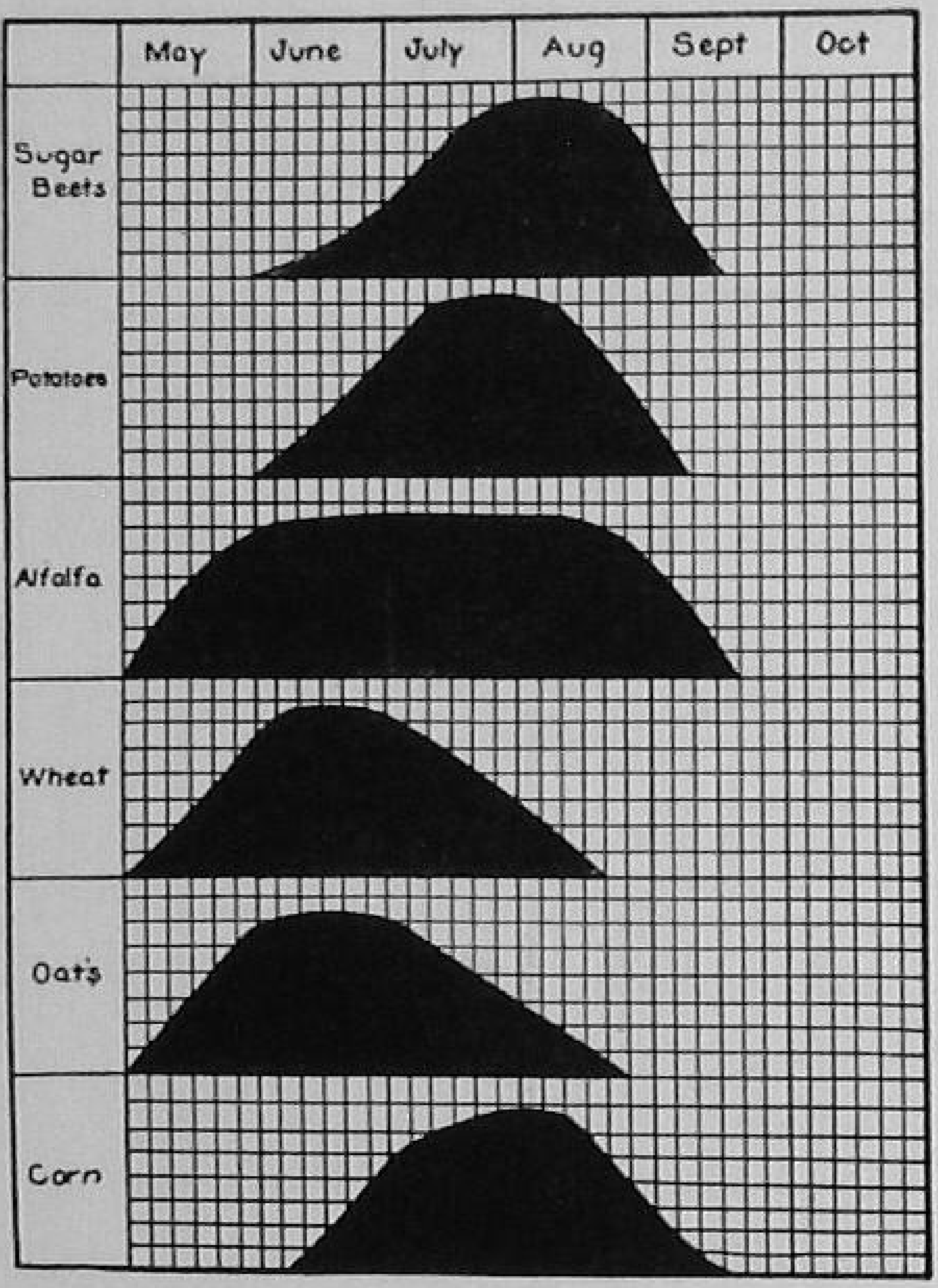


FIG. 157. Representing the seasonal use of water by various crops in Cache Valley, Utah. (*Utah Agr. Exp. Sta. Bul.* 173.)

213. Seasonal Use of Water by Different Crops Irrigators may select their crops, to some extent, on the basis of time at which water will be available. In valleys having no storage reservoirs the larger quantities of water are available early during the season. From the beginning of the crop-growing season until late in June or early July the streams are fed by the melting of snow banks and drifts in the mountains, and the water supply is much larger than it is later during the summer. Under such conditions, alfalfa, wheat, and oats may well be produced, as each of these crops requires large amounts of water in May and June. Canning peas may be matured before the water shortage begins. Alfalfa continues to grow throughout the late summer months provided water is available. Sugar beets, potatoes, and corn require very little water early in the season, but during the late summer months these crops need an abundance of water. Unless late-season water is assured it is inadvisable to attempt to grow sugar beets and potatoes. The time periods at which the more important crops of Cache Valley, Utah, use water, and also the rates of use at different periods, have been well illustrated by Harris, as shown in Fig. 157.

214. Available Water Supply Irrigation during the dormant or non-growing season, in many localities, is an economical means of storing

water in the soil for future use. During the growing season farmers sometimes apply water in copious quantities immediately after heavy rains which increase the flow in rivers and creeks and thus make available for short periods of time rather large quantities of water for irrigation. It is desirable to build surface reservoirs, both large and small, in which to store water that becomes available from sudden torrential rains or that is available only during the fall, winter, or spring, when it must be stored, used, or lost. As a general rule, water which is used in irrigation at times when not really needed by crops is used less efficiently than it would be if it were possible to apply it to the soil when most needed by crops. In localities where storage of water in surface reservoirs is impracticable because of high costs and lack of suitable natural facilities, it is advantageous to use the soil as storage reservoir and to apply water whenever it is available as a means of storing it for future use. Bench or table lands should be irrigated sparingly, particularly lands having shallow surface soils which are underlain by coarse-textured sands and gravels, provided the objective is to store water only in the capillary form. Some areas can be benefited by applying depths of water during the dormant season sufficient to saturate the subsoil gravels and cause the water table to rise to an elevation near the land surface. Where it is not feasible to pump the ground water to the surface during the irrigation season, excessive depths applied during the dormant season may cause appreciable damage by waterlogging the soil.

215. Fall Irrigation The need for fall irrigation of lands that are used to produce annual crops, such, for example, as grains, potatoes, sugar beets, beans, and peas, is determined largely by the precipitation. In localities that normally have enough fall and winter precipitation to raise the moisture content of the soil to field capacity to the full depth of the root zone after a crop has been harvested, there is little, if any, direct advantage in fall irrigation, except during years of abnormally low precipitation. These localities are relatively few in number, and the area they include is comparatively small. There are many places in which the fall and winter precipitation is insufficient to moisten the soil fully. In most of these localities the streams yield, during the fall months, water that flows past the lands and is wasted unless applied to the land. Fall irrigation under such conditions is a means of saving water and of placing the land in favorable condition for germination of seeds and early growth of crops during the following season.

Alfalfa grown on well-drained soils may be irrigated in the fall, and fall irrigation of meadow forage crops and of pasture lands is usually

desirable if, without irrigation, the soils become very dry. In the practice of irrigation during the fall, winter, or early spring it is important to guard against the use of excessive depths of water. As shown in Chapter 9 there are definite limitations to the capacity of any soil to retain water. In the Rocky Mountain states some irrigators, during the fall, permit water to run on their lands many days and sometimes weeks. This practice is injurious both to the land irrigated and to the lower-lying areas to which much of the excess water seeps.

216. Winter Irrigation At the higher elevations and in the colder parts of irrigated regions, winter irrigation is of little if any practical importance. The frozen soils absorb water slowly, if at all, and it is difficult to spread water over the fields effectively. Furthermore, some crops are injured by winter irrigation in cold climates.

In the milder climates, however, winter irrigation may be practiced advantageously as a means of saving water that would otherwise be lost. Forage and pasture crops use relatively small amounts of water during the winter months. The irrigation of orchards during the dormant season is considered in Chapter 16.

217. Early Spring Irrigation Some arid-region lands need irrigation during the early spring months in order to supply the moisture essential to satisfactory germination and early growth of annual crops. Arid-region streams usually have ample water to meet the needs for early spring irrigation. Even where the discharge of the streams at high mountain elevations is held in storage reservoirs, enough water is available from the rains and melting snows on lower elevations to supply the needs for early spring irrigation. The value of early spring irrigation as a means of storing available water in the root-zone soil is not yet fully realized. Irrigators are frequently misled by the fact that the spring rains moisten the soil to a depth of 9 to 15 in. Some consider the soil "wet enough" when, in fact, there is 3 to 5 ft of dry soil below the moist surface soil.

Use of the soil auger or of the soil tube described in Chapter 9 will enable irrigators to decide intelligently the needs of soils for early spring irrigation. Although it is highly desirable to save water by applying it to inadequately moistened soils it is quite undesirable early in the spring to irrigate soils that are already moistened to field capacity.

Fully moistened soils in which the water table is at a shallow depth may be injured rather than benefited by early spring irrigation. Under such conditions it is better to waste water in natural streams than to apply it to the soil.

14
Consumptive Use of Water

by

HARRY F. BLANEY* and ORSON W. ISRAELSEN

The consumptive use of water involves problems of the water supply, both surface and underground, as well as those of the management and economics of irrigation projects. It has become a highly important factor in the arbitration of controversies over major stream systems where the public welfare of valleys, states, and nations is involved. Before the available water resources of a drainage basin in arid and semiarid regions can be satisfactorily ascertained careful consideration must be given to the consumptive-use requirements for water in various sub-basins.

Efficient use of water by farm crops is everywhere important. The humid-climate farmer depends on the available water stored in his soil and on the crop-season rainfall for his crops. Not infrequently his production is limited because of insufficient water during critical periods. Of even greater importance is the efficient use of water in arid and semiarid regions.

The rapid growth of American irrigation during the first half of the twentieth century has developed a keen public interest in a study of the disposal of irrigation water. The pioneers in irrigation had little opportunity to fully ascertain what became of the water which they applied to their lands. That they lost some water by surface runoff was obvious; that some water was absorbed by the crops they grew was likewise apparent; but that large volumes of water percolated deeply into the soil below the root zone was to them merely speculation. However, the gradual rise of water tables, with resulting enlargement of natural springs and the development of new springs and the seepage return to stream channels, gave increasing evidence concerning the magnitude of losses of water through deep percolation. More-

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over, it was found through years of experience that much less water need be applied to the farms to produce profitable crops than was formerly believed necessary, and the areas of land properly irrigated by the water from a given stream were greatly increased without any apparent increase in the available water supply. Water formerly consumed by natural vegetation and evaporation under virgin conditions was now used by agricultural crops. Such increase in area of irrigated land could not continue without limit for some water was actually consumed by the growing crops.

218. Definitions and Analysis The term "consumptive use," as originally applied to irrigation, was defined as a seasonal loss of water in acre-feet per acre irrigated. Among the first published writings dealing directly with the consumptive use, a report of a committee of the American Society of Civil Engineers, by Harding, Israelsen, et al., entitled *Consumptive Use of Water in Irrigation,* is noteworthy.

The committee proposed certain definitions for consumptive use of water in a basic sense, and for the farm, the project, and the valley. It also reviewed previous estimates of consumptive use for large river systems.

In the Upper Rio Grande Joint Investigation of 1936 and the Pecos River Joint Investigation of 1941, the Division of Irrigation of the United States Department of Agriculture and the National Resources Planning Board defined consumptive use (evapo-transpiration) as follows:

> *Consumptive use* (*evapo-transpiration*) is the sum of the volume of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specified time. It may be expressed in acre-inches per acre (depth in inches) or acre-feet per acre (depth in feet). For a 12-month year, consumptive use is usually expressed in acre-feet per acre (or feet). Considered from a valley-wide standpoint, consumptive use includes all transpiration and evaporation losses from lands on which there is growth of vegetation of any kind, whether agricultural crops or native vegetation, plus evaporation from bare land and from water surfaces.

This definition was adopted with minor changes by the Committee on Irrigation of the American Society of Agricultural Engineers in 1939.

219. Conditions Affecting Consumptive Use of Water Evapo-transpiration is influenced by temperature, irrigation practices, length of growing season, precipitation, and other factors. The volume of water transpired by plants depends in part on the water at their disposal, and also on temperature and humidity of the air, wind movement, the

intensity of sunlight, the stage of development of the plant, its foliage, and the nature of its leaf.

The volumes of irrigation water are not always dependable indicators of the actual water requirements of crops; nevertheless, knowledge of water applied helps in considerations leading to authentic estimates of consumptive use. Many factors may operate, singly or in combination, to influence water usage, and their effects are not necessarily constant but may fluctuate from year to year as well as from place to place. Some of these may be grouped as: (1) natural; (2) physical (as related to the character of equipment, structures, and required methods of handling water); (3) farm managerial; and (4) economic, legal, and administrative (sometimes reflecting mere long-established customs).

Natural factors include climate, water supply, soils, and topography. Differences in temperature from year to year usually cause differences in consumptive use; abnormally low temperatures may retard plant development, and usually high temperatures produce dormancy. Increasing wind movement normally increases evaporation; increased humidity and cloudiness reduce it. Hail may damage crops and so reduce their rates of transpiration.

The growing season is frequently considered the time between killing frosts, but for annual crops it is shorter than the frost-free period, as crops are planted after frosts are past and mature before they recur. For most perennial crops growth starts as soon as the maximum temperature stays well above the freezing point for any extended period of days and continues so throughout the season in spite of later freezes.

Physical factors include the main water-supply ditch, pipe, or other conduit for the farm, the division of the farm into fields suitable for irrigation and cropping, all permanent farm ditches, the preparation of the surface of each field to receive water, and the method of application of water.

Annual consumptive use varies with types of management and land use, which are influenced by economic factors. These factors may change crop distribution and methods of irrigation. Thus, a change from cotton to alfalfa increases transpiration. Consumptive use by native vegetation of non-cropped land is fairly constant from year to year where the water supply is adequate, but surface evaporation increases in wet years because of the expansion of water surface and moist soil areas. In irrigated valleys irrigation is usually lavish when the supply is abundant, and increased waste and return flow are consequently available for non-productive consumption; so also

is soil evaporation increased from the cropped lands. Plant diseases and pests reduce consumptive use by inhibiting plant growth. The spread of noxious weeds may reduce the area irrigated if crops cannot be grown in infested areas. Indirect results of infestation may appear in widespread changes in crops.

Size of farm may affect water usage appreciably since borders or furrows, irrigation heads, and rotations may be adjusted differently to acreages relatively large or small.

Though economic considerations enter into the farm management group, such subjects as cost of water, manner of payment, and permissible waste are considered of essentially economic importance. When a farmer pays for water on an acreage basis he has little inducement to economize in its use, but if he buys water by the acre-foot, or pumps it from his own well, any saving he effects during the season reduces his water bill proportionately.

220. Evaporation from Soils Areas of moist soils, where the water table is close to the ground surface, exist in many localities. Where the water table is near the ground surface, evaporation from the soil is almost equal to the evaporation from a free water surface, whereas with the water levels at greater depths below the surface the evaporation from soil decreases until it reaches about zero when moisture no longer reaches the surface by capillary action.

At the Denver Field Laboratory of the Division of Irrigation of the United States Department of Agriculture, Sleight made a comparison between the evaporation from a water surface and that from different soil and river-bed materials under varying depth to water table by tank experiments. Table 39 gives the results obtained from fine sandy loam and also from river-bed sand.

Where irrigation water is applied by the flooding methods large amounts of water are lost by direct evaporation from the soil surface without passing through the roots, stems, and leaves of the plants. Some authorities speak of transpiration as evaporation from the plant leaves; however, not all the evaporation from leaf surfaces results from transpiration. After light showers during the growing season the water lost by direct evaporation from the leaf surfaces and from the ground surface serves little, if any, useful purpose. Similarly the water lost by direct evaporation from the ground surface after irrigation serves no useful purpose. It should therefore be reduced as much as practical.

221. Reducing Evaporation Many experiments have been conducted, in humid and in arid regions, concerning the effect of cultivation on

TABLE 39

EVAPORATION FROM WATER SURFACE AND FROM DIFFERENT SOILS WITH WATER TABLE AT VARIOUS DEPTHS BELOW THE SURFACE IN TANKS 2 FT IN DIAMETER

Period Ending	Evaporation from Water Surface, Inches	Evaporation from Soil, Inches					
		Fine Sandy Loam					
		Water Table Depths Below the Soil Surface					
		4 in.	16 in.	28 in.	38 in.	43 in.	50 in.
Aug. 30*	3.84	2.98	2.69	2.19	1.23	0.24	0.19
Sept. 15	4.77	4.37	4.09	3.12	1.98	0.37	0.32
25	2.10	1.81	1.67	1.44	0.30	0.16	0.16
29	0.91	1.04	0.84	0.69	0.43	0.11	0.16
Oct. 4	1.23	1.14	0.97	0.58	0.30	0.10	0.10
Total	12.85	11.34	10.26	8.02	4.24	0.98	0.93
Percentage	100.0	88.2	79.8	62.4	33.0	7.63	7.24
		River-Bed Sand					
		Water Table Depths Below Soil Surface					
		3 in.	6 in.	$10\frac{1}{2}$ in.	24 in.		
Aug. 4†	1.01	0.62	0.67	0.50	0.19		
9	1.12	1.07	0.80	0.74	0.15		
12	0.85	0.90	0.80	0.69	0.18		
15	0.69	0.35	0.32	0.28	0.04		
17	0.54	0.34	0.29	0.21	0.04		
29	3.54	2.54	2.42	2.22	0.80		
Sept. 12	4.44	2.71	2.62	2.47	0.34		
25	2.83	2.16	2.06	1.82	0.25		
29	0.91	0.42	0.40	0.36	0.12		
Oct. 4	1.23	0.69	0.67	0.63	0.00		
10	0.99	0.54	0.54	0.50	0.00		
16	0.88	0.62	0.62	0.50	0.16		
Total	18.93	13.06	12.21	10.92	2.27		
Percentage	100.0	69.0	64.5	57.7	11.3		

* The period began Aug. 17.

† The period began July 31.

direct evaporation of water from soils, but there are still rather decided differences in opinion.

Pioneer American irrigation research workers found that evaporation could be greatly decreased by the formation of an earth mulch through cultivation. The early belief that the upward flow of capillary water was very great and that a blanket of cultivated dry soil would check it has been widely accepted and commonly taught.

In 1917 Call and Sewell pointed out that many of the experiments that show saving of water through cultivation were conducted on field

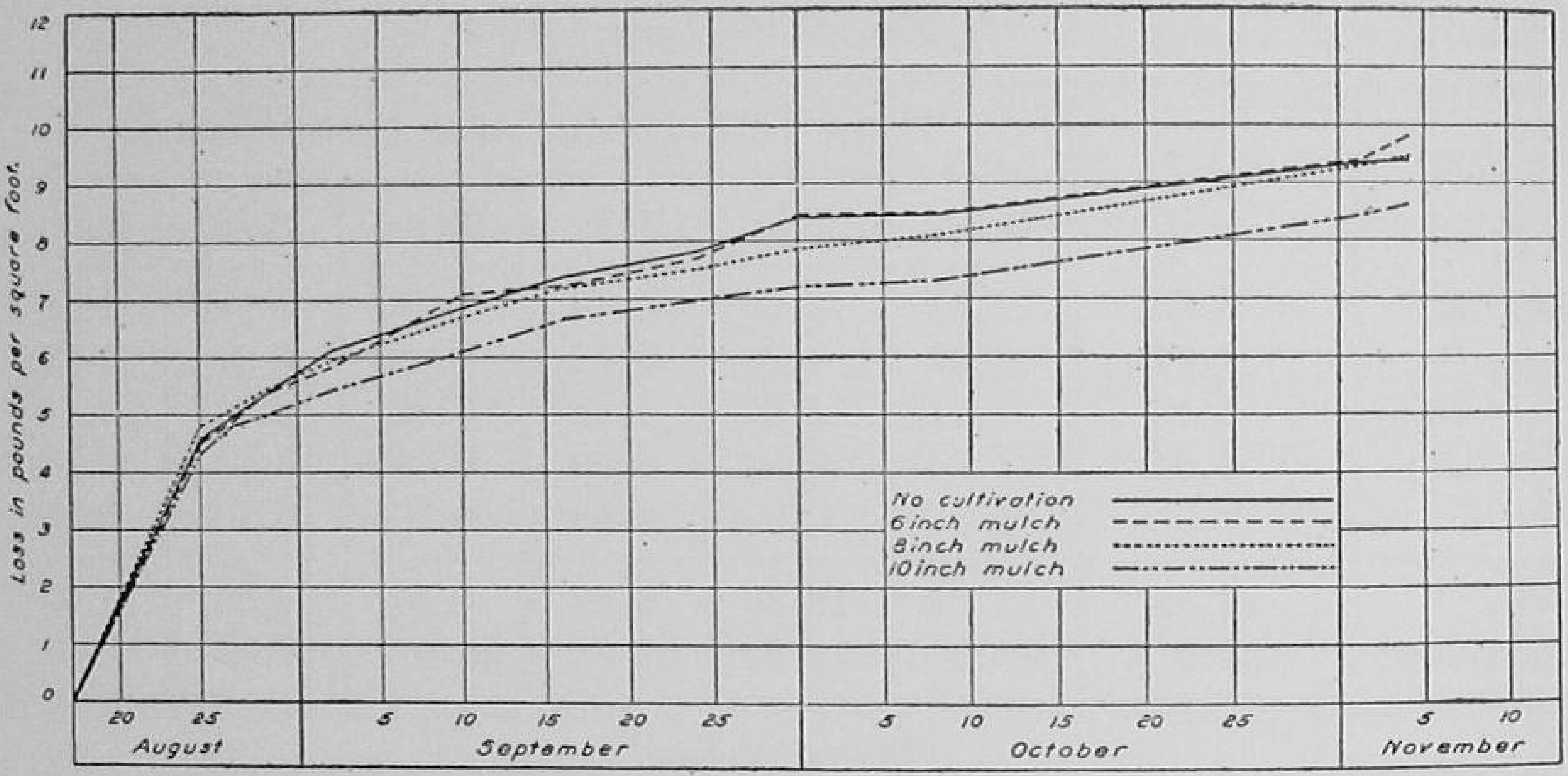

FIG. 158. Loss of water by evaporation directly from the surface of bare soils in tanks at Mountain View, 1921. (Calif. Agr. Exp. Sta., *Hilgardia*, Vol. 2, No. 6.)

soils having a shallow water table, or with soil columns in a laboratory where the soil was either saturated at the outset or kept in contact with free water. Alway and McDole have conducted experiments on moisture movement under conditions quite independent of free water or of a water table and have found a relatively slight movement vertically upward. Veihmeyer conducted detailed studies on the influence of cultivation on evaporation losses from soils not in contact with free water. Evaporation losses from tanks treated in four different ways are presented in Fig. 158, which shows that the losses from tanks not cultivated and from those cultivated to a depth of 6 in. are practically identical. The 8-in. depth of cultivation shows slight decreases, and the 10-in. depth of cultivation slightly greater decreases.

Veihmeyer concluded that cultivation did not influence the losses of moisture by evaporation from the bare surfaces of the soils in the tanks and in the field plots under observation.

Shaw studied the influence of the soil mulch in the laboratory and concluded that: "The soil mulch can reduce the loss of soil moisture

only when the water, perched or permanent, is within capillary rise of the surface."

The recent studies seem to throw considerable doubt on the advantages of soil mulches for conserving water through reduction of evaporation losses from soils that are not excessively wet or in contact with a water table at a shallow depth.

Broad general conclusions concerning the influence of cultivation on direct evaporation losses from soils may be misleading. The large number of variable factors involved—notably the differences in distances to free water sources, in original moisture content of unsaturated soils, in texture, structure, and water conductivity—make it hazardous to generalize.

222. Transpiration The process by which water vapor escapes from living plants, principally the leaves, and enters the atmosphere is known as transpiration. Often transpiration is the largest component of evapo-transpiration. Direct evaporation from moist soil, from water surfaces, and from rain water intercepted by leaves constitutes the remainder of evapo-transpiration use. Knowledge concerning transpiration encourages more efficient use of water in irrigation.

During the growing period of a crop there is a continuous movement of water from the soil into the roots, up the stems, and out of the leaves of the plants. Water thus moving acts as a carrier of essential plant food substances from the soil to the various parts of the plant. The velocity of the water flowing through the plant varies widely from 1 to 6 ft per hr; but, under conditions of unusually high temperature, dry atmosphere, and wind, the velocity of the stream may be greatly increased. Transpiration is vitally essential to plant life. A very small proportion of the water absorbed by the roots is retained in the plant. To the irrigation farmer the velocity of water flow through the plant and the volume of water that annually evaporates from the leaf surfaces are of special importance. If the rate of evaporation at the leaves is for a brief period greater than the rate of absorption by the roots, wilting occurs and the growth of the plant is impeded. On the other hand, if the conditions are such as to stimulate excessive transpiration, without also conveying substantial amounts of plant food substances into the plant and favoring rapid manufacture of food in the plant leaves, the available water is not used efficiently. That plant growth is not necessarily proportional to transpiration is of fundamental importance to arid-region agriculture.

Transpiration of water by citrus, walnut, deciduous, alfalfa, cotton, and other crops has been measured by the Division of Irrigation

and Water Conservation, SCS, cooperating with the agricultural experiment stations in several states, using the soil moisture method. Soil samples were taken from selected plots in farms to depths of 5 to 10 ft below the mulch, and determinations were made of the

TABLE 40

Transpiration Use for Citrus, Peaches, Walnuts, and Cotton in California Areas

Month	Transpiration Use, Inches per Month and per Year or Season							
	Mature Citrus				Peaches	Walnuts	Cotton	
	Santa Ana (1)*	Azusa (2)	Los Angeles (3)	Los Angeles (4)	Ontario (5)	Santa Ana (6)	Shafter (7)	Shafter (8)
January	1.0	1.3	0.8	1.1				
February	1.0	1.2	1.1	2.2				
March	0.8	1.5	1.4	2.3				
April	1.3	1.9	1.7	4.0	0.5	0.5	0.2	0.2
May	1.9	2.1	2.2	4.4	3.0	4.1	1.0	1.0
June	2.7	2.2	2.6	4.6	6.2	3.8	3.2	3.0
July	3.1	3.3	2.9	4.0	8.0	6.4	7.7	7.6
August	3.0	3.1	2.7	3.4	6.0	5.3	8.9	5.8
September	2.6	1.9	2.6	2.8	2.7	3.2	5.5	3.5
October	1.8	2.2	2.4	2.6	0.9	1.7	3.0	2.3
November	1.3	1.5	1.6	2.0	0.2			
December	1.1	1.3	1.3	1.6				
Annual	16.4	23.5	23.3	35.0	27.5	25.0	29.5	23.4

	Year	Cover Crop	Authority
* (1)	1929	None	S.H. Beckett
(2)	1929–1930	Winter	H.F. Blaney, C.A. Taylor
(3)	1940	Winter	H.F. Blaney
(4)	1940	Entire year	H.F. Blaney
(5)	1928	None	H.F. Blaney, C.A. Taylor
(6)	1928–1929	None	S.H. Beckett
(7)	1928	Ample moisture entire season	S.H. Beckett, C.F. Dunshee
(8)	1928	Ample moisture first half season; deficiency last half	S.H. Beckett, C.F. Dunshee

amount of moisture extracted from each foot of soil within the root zone. Examples of monthly rates of transpiration for four crops in California are shown in Table 40.

223. Transpiration Ratio The ratio of the weight of water that is absorbed by, conveyed through, and transpired from the plant to the

weight of dry matter produced by the plant is defined as the *transpiration ratio*. Dry matter is that part of the plant which remains when all the water has been driven from the plant by heat. In determining the weight of dry matter it is customary to use only those parts of the plants which are harvested. For example, the roots and the vines of potatoes, the leaves of sugar beets, the roots of grain plants such as wheat, oats, barley, rye, and the roots of forage crops are excluded. There are exceptions to this general rule. In some investigations the entire plant—roots, stems, leaves, seed, and all—is used. Unless otherwise stated, it will be understood that only the plant parts ordinarily harvested are included. Some reports of transpiration ratio studies are not specific as to the parts of plant used in determining the weight of dry matter. To make transpiration ratio comparisons reliable it is essential that the basis of computations be fully given. Transpiration ratios as a rule are determined by growing plants in large tanks or cylinders filled with soil. In some experiments the tanks are weighed at frequent intervals to determine the amount of water transpired; in others an artificial water table is kept at a given elevation, and the water transpired is determined indirectly by measuring the volume of water necessary to maintain the water table at a constant elevation. Some experimenters have devised special means of preventing evaporation losses; others have estimated evaporation losses from the tanks in various ways and deducted the estimated evaporation losses from total losses to arrive at the amounts transpired. All experimenters using tanks have prevented deep percolation losses. The transpiration ratio ranges from less than 200 to more than 1000 lb of water for each pound of dry matter produced.

224. Methods of Determining Consumptive Use Various methods have been used to determine the amount of water consumed by agricultural crops and natural vegetation. Regardless of the method, the problems encountered are numerous. The source of water used by plant life, whether from precipitation alone, irrigation plus rainfall, or ground water plus precipitation, is a factor in selecting a method. The principal methods are: tank and lysimeter experiments, field experimental plots, soil moisture studies, analysis of climatological data, integration method, and inflow-outflow for large areas.

These six methods of measuring consumptive use of water are described in the following articles, and typical results by each method are presented in accompanying tables.

225. Tank and Lysimeter Experiments The reliability of consumptive-use determinations by means of tanks or lysimeters is dependent

on nearness of reproduction of natural conditions. Artificial conditions are caused by the limitations of soil, size of tank, regulation of water supply, and sometimes environment.

Tanks should be placed in surroundings of natural growth of the same species, that is, in their natural environment, so that consumptive use of water will presumably be the same as for similar growth outside the tank. It has been found that all tank vegetation must be protected from the elements by surrounding growth of the same species.

TABLE 41

Consumptive Use of Water by Wheat and Potatoes in Tanks, Wright Station, San Luis Valley, Colorado, 1936

Tank Number	Crop	Inches Each Month and during the Season				
		June	July	August	September	Total
1	Wheat*	3.41	6.64	4.05	....	14.10
2	Wheat*	3.67	6.70	3.64	....	14.01
3	Potatoes†	.70	7.93	5.66	1.44‡	15.73
4	Potatoes	1.74	6.43	5.25	1.60‡	15.02

* Water table varied from 24 to 53 in. Crop harvested Sept. 1.
† Water table varied from 20 to 54 in. Crop harvested Sept. 15.
‡ Sept. 1 to Sept. 15.

Weighing is the precise means of determining the consumptive use from tanks. This method was used by the Division of Irrigation, United States Department of Agriculture, as early as 1903 in cooperation with the University of California and other agricultural experiment stations. However, conditions and facilities will not always permit the weighing of tanks. Soil tanks equipped with Mariotte water supply tanks have proved successful in evapo-transpiration measurements from water tables at various depths. The double-type soil tanks, with an annular space between the inner and outer shells, are considered best.

The Mariotte supply system furnishes water as needed to maintain a fixed water level in the annular space in the soil tank. The amount of water withdrawn is determined by differences in daily or weekly readings of the glass gage attached to the supply tank. The value in the use of Mariotte-equipped tank lies in the ease with which periodic measurements of water used may be made, as it is automatic in operations.

Tables 41 and 42 show the results of tank experiments made by Blaney and Israelsen on consumptive use by wheat, potatoes, and cotton in the Upper Rio Grande Basin in Colorado and New Mexico.

Results of some of the measurements made by Criddle and Marr in Idaho are shown in Table 43.

226. Field Experimental Plots Tank and lysimeter experiments for individual crops do not always represent the natural conditions of the soil, as there are many ways of preparing and arranging soil material. Measurements by soil moisture studies in field plots are usually more dependable than measurements with tanks or lysimeters.

TABLE 42

CONSUMPTIVE USE OF WATER BY COTTON IN TANKS, STATE COLLEGE, NEW MEXICO, 1936

Period	Number of Days	Inches* during Various Time Periods				Precipitation, Inches
		West Tank	East Tank	Average		
				Period	Per 30 Days	
June 6 to July 5	19	3.13	5.94	4.53	7.15	0.14
July 5 to Aug. 8	34	8.61	8.26	8.44	7.45	1.58
Aug. 8 to Sept. 5	28	6.53	6.63	6.58	7.05	1.33
Sept. 5 to Nov. 7	63	7.69	11.39	9.54	4.54	2.49
Total	144	25.96	32.22	29.09	....	5.54

* Including precipitation. No water table.

The early measurements of consumptive use were made on selected field plots of irrigated crops where the water table was at a considerable distance below the surface.* The procedure was to measure the volume of water applied to the plot at each irrigation and to measure any surface runoff that might occur. In order to avoid percolation of water below the plant root zone it was necessary to apply the water in small depths, not to exceed 5 in. in a single irrigation on ordinary soils. However, in some experiments deep percolation occurred. In most of the field determinations the runoff has been either carefully measured or reduced to zero by proper preparation of experimental plots. Precise measurements of the change in soil moisture were not undertaken in most of the early studies.

Widtsoe pioneered the measurement of consumptive use in field plots, beginning in 1902. His work was done on land having a water table about 75 ft below the surface; and hence it is reasonably safe to conclude that the crops obtained no ground water and that the crop-season rainfall, the draft on stored capillary soil moisture, and

* It is usually impracticable to measure the water absorbed by the crop from a high water table.

the irrigation water furnished all the water to which the crops had access. There was no runoff from the experimental plots used by Widtsoe, and the deep percolation losses were not measured. However,

TABLE 43

SUMMARY OF AVERAGE ANNUAL CONSUMPTIVE USE OF WATER BY WHEAT AND ALFALFA GROWN IN TANKS WITH A HIGH WATER TABLE AT BONNER'S FERRY, IDAHO

Period of Records, Yr	Number of Tanks	Soil Type	Depth to Water, Ft	Average Consumptive Use, Ft	Yield* per Acre	
					Bu	Tons
Wheat						
8	3	Mineral	1.25–1.75	2.19	38	...
11	3	Mineral	2.25–2.75	1.43	43	...
6	3	Mineral	3.25–3.75	1.32	46	...
9	5	Organic	1.25–1.75	2.05	14	...
11	5	Organic	2.25–2.75	1.80	44	...
4	5	Organic	3.25–3.75	1.66	39	...
Alfalfa						
1	2	Mineral	1.25–1.75	2.72	..	4.1
4	2	Mineral	1.75–2.25	3.05	..	8.1
5	2	Mineral	3.25–3.75	2.88	..	8.7
3	4	Organic	1.25–1.75	3.87	..	7.1
7	4	Organic	1.75–2.25	3.16	..	6.6
10	4	Organic	3.25–3.75	2.66	..	7.8

* Tank yields per acre generally higher than valley averages, especially for alfalfa.

these losses have been assumed to be negligible. Widtsoe measured these sources of water for 14 crops during the 10-yr period, 1902–1911 inclusive. The crop-season rainfall was 0.42 ft, and the seasonal draft on capillary moisture in the upper 8 ft of soil varied from 0.10 ft for corn to 0.83 ft for alfalfa. Irrigation water was applied, varying from 0.42 ft to 5 ft, and wide variations in crop yields were obtained. The yields obtained by Widtsoe have been plotted against the total water used, and, as a basis for arriving at the consumptive use, those yields were selected which appear to be most profitable. With nearly every crop, the yield increased rapidly to a certain point with increase of water used, and then either decreased with further increase in water or increased very slowly. At this "break in the curve," the use is considered as consumptive use.

Widtsoe's work indicates the importance of yield in determining the consumptive use. It is also important to keep in mind the fact that deep percolation losses from the plots on which Widtsoe worked would

result in observed magnitudes of use higher than the true ones. It is far more probable that the given values are too high rather than too low.

Snelson, working on field plots in Brooks, Alberta, Canada, used moderate quantities of water in single applications and made careful measurements of soil moisture to a depth of 6 ft at the beginning and at the end of the growing season. Under his methods percolation loss in all probability was very small, if not zero. If percolation losses were zero, then according to Snelson's experiments with wheat on the more fertile soil the consumptive use varied from 0.85 ft to 1.82 ft as the crop yield varied from 10 to 50 bu per acre. For oats on the more fertile plots the consumptive use ranged from 0.72 ft to 1.75 ft as the yield varied from 40 to 135 bu per acre. Barley required a consumptive use from 1.25 to 1.60 ft for yields ranging from 40 to 51 bu per acre, and for alfalfa the use varied from 1.00 to 2.62 ft for yields ranging from 1.0 to 5.7 tons per acre.

Powers has made many field plot measurements of consumptive use in Oregon. Experimenting with alfalfa in the Willamette Valley, using moderate irrigation, he found values from 1.4 to 2.0 ft accompanying yields of 4.1 to 5.2 tons per acre. The consumptive use for clover was approximately the same as that for alfalfa. Moisture determinations were made to a depth of 6 ft at the outset, but as most of the borings showed a water penetration to only 4 ft the later borings were not made below this depth except in connection with a few very heavy irrigations.

Harris and others made measurements of depth of water applied and yield of field plots, but deep percolation losses probably occurred in some instances.

227. Soil Moisture Studies Consumptive use of water for various crops has been determined by intensive soil moisture studies. This method is usually suitable for areas where the soil is fairly uniform and the depth to ground water is such that it will not influence the soil moisture fluctuations within the root zone. Soil samples are taken by means of a standard soil tube or auger before and after each irrigation with some samples between irrigation in 1-ft sections in the major root zone. Usually a great number of soil samples must be taken. The work is greatly expedited by using an air hammer to drive the soil tube and a jack to withdraw it from the soil. The equipment consists of a compressed-air unit, soil tube, and soil tube jack. For average soil, where the depth of sampling does not exceed 7 ft, a hand hammer will usually drive the soil tube satisfactorily.

Standard laboratory practices are used in determining the moisture content of the soil samples. The samples are weighed and dried in an electric oven at 110° C, and the dry weights determined. The water content of a sample is expressed as percentage of the oven-dry weight of the soil. From the moisture percentage thus obtained the quantity of water in acre-inches per acre removed from each foot of soil is computed by means of the formula in Chapter 9.

The acre-inches of water extracted from the soil is computed for each period and later reduced to equivalent losses in inches for a 30-day period. The 30-day-period losses may then be plotted, and a use-of-water curve for the season obtained. The average use of water for each month is taken directly from the curve. This method was used by Beckett and Blaney in southern California in 1925 in determining transpiration use of citrus and avocado trees and later was employed to measure monthly consumptive use by alfalfa and other crops. Examples of consumptive use as determined by this method are shown in Table 44.

Ground-water-table fluctuations provide a basis for estimating consumptive use of water. Evapo-transpiration losses are indicated by daily rise and fall measurements of water table from wells equipped with water-stage recorders. This method has been used by the Geological Survey in Arizona, Utah, and other areas where conditions were favorable, but usually it is not suitable for determining use by agricultural crops.

228. Analysis of Climatological Data Formulas for estimating consumptive use, based on climatic factors, have been found to give reasonable results. Irrigation engineers have utilized temperature data in estimating annual valley consumptive use of water. Hedke developed the effective heat method on the Rio Grande. By this method consumptive use is estimated from a study of the heat units available to the crops of a particular valley. It assumes that there is a linear relation between the water consumed and the quantity of available heat. In Bureau of Reclamation studies conducted from 1937 to 1940 by Lowry and Johnson a similar method was suggested which the Bureau has adopted quite generally in making its estimates of valley consumptive use. This method also assumes a direct linear relation between consumptive use and accumulated daily maximum temperatures above 32° F during the growing season.

The Division of Irrigation of the Soil Conservation Service has determined unit rates of consumptive use by various crops in the Pecos River Basin, New Mexico and Texas; the Salinas Valley, California;

the Upper Colorado River Basin; and other areas of the West, by analyzing climatological data and irrigation practices. In 1939–1941, in connection with the Pecos River Joint Investigation of the National

TABLE 44

CONSUMPTIVE USE OF WATER FOR IRRIGATED CROPS AS DETERMINED BY SOIL MOISTURE STUDIES IN ARIZONA, CALIFORNIA, AND NEBRASKA

Month	Inches Each Month and the Season				
	Alfalfa (1)*	Beets (2)	Cotton (3)	Peaches (4)	Potatoes (5)
April	3.3		1.1	1.0	
May	6.7	1.9	2.0	3.4	
June	5.4	3.3	4.1	6.7	0.7 (6)
July	7.8	5.2	5.8	8.4	3.4
August	4.2	6.9	8.6	6.4	5.8
September	5.6	5.8	6.7	3.1	4.4
October	4.4	1.1 (7)	2.7	1.4	
Season	37.4	24.2	31.0	30.4	14.3

	YEAR	LOCATION	AUTHORITY
* (1)	1940	Los Angeles, Calif.	H. F. Blaney
(2)	1932–1935	Scottsbluff, Neb.	Leslie Bowen
(3)	1936	Mesa Expt. Farm, Ariz.	Karl Harris
(4)	1928	Ontario, Calif.	H. F. Blaney
(5)	1932–1935	Scottsbluff, Neb.	Leslie Bowen
(6)	(June 20–30, inclusive)		
(7)	(Oct. 1–15, inclusive)		

Resources Planning Board, the Division of Irrigation found that evaporation, mean monthly temperature, humidity, monthly percent of daytime hours, growing season, monthly precipitation, and irrigation data could be utilized to estimate rates of consumptive use. Blaney and Morin developed empirical formulas from the Pecos River studies for estimating unit annual values of evaporation from free-water surfaces and consumptive use by vegetation subsisting on ground water. This method is applicable to those areas in which there is ample water to take care of evaporation and transpiration. Blaney and Criddle modified the Pecos formula by eliminating the humidity factor and extending the study to irrigated crops.

By multiplying the mean monthly temperature t by the monthly percentage of daytime hours of the year p, there is obtained a monthly consumptive use factor f.

Expressed mathematically,

$$U = KF = \text{sum of } kf \tag{51}$$

TABLE 45

DAYTIME HOUR PERCENTAGES FOR EACH MONTH OF THE YEAR FOR LATITUDES 26 TO 48 DEGREES NORTH OF EQUATOR*

Month	Latitudes in Degrees North of Equator											
	26	28	30	32	34	36	38	40	42	44	46	48
	%	%	%	%	%	%	%	%	%	%	%	%
January	7.49	7.40	7.30	7.20	7.10	6.99	6.87	6.76	6.62	6.49	6.33	6.17
February	7.12	7.07	7.03	6.97	6.91	6.86	6.79	6.73	6.65	6.58	6.50	6.42
March	8.40	8.39	8.38	8.37	8.36	8.35	8.34	8.33	8.31	8.30	8.29	8.27
April	8.64	8.68	8.72	8.75	8.80	8.85	8.90	8.95	9.00	9.05	9.12	9.18
May	9.38	9.46	9.53	9.63	9.72	9.81	9.92	10.02	10.14	10.26	10.39	10.53
June	9.30	9.38	9.49	9.60	9.70	9.83	9.95	10.08	10.21	10.38	10.54	10.71
July	9.49	9.58	9.67	9.77	9.88	9.99	10.10	10.22	10.35	10.49	10.64	10.80
August	9.10	9.16	9.22	9.28	9.33	9.40	9.47	9.54	9.62	9.70	9.79	9.89
September	8.31	8.32	8.34	8.34	8.36	8.36	8.38	8.38	8.40	8.41	8.42	8.44
October	8.06	8.02	7.99	7.93	7.90	7.85	7.80	7.75	7.70	7.63	7.58	7.51
November	7.36	7.27	7.19	7.11	7.02	6.92	6.82	6.72	6.62	6.49	6.36	6.22
December	7.35	7.27	7.14	7.05	6.92	6.79	6.66	6.52	6.38	6.22	6.04	5.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* From "Sunshine Tables," *United States Weather Bureau Bulletin* 805, Edition of 1905.

where U = consumptive use of crop; inches for a given time period.
F = sum of the monthly consumptive-use factors for the period (sum of the products of mean monthly temperature and monthly percent of annual daytime hours) $(t \times p)/100$.
K = empirical coefficient (annual, irrigation season or growing season).
t = mean monthly temperature in degrees Fahrenheit.
p = monthly percent of daytime hours of the year. (See Table 45.)
f = monthly consumptive-use factor, $(t \times p)/100$.
k = monthly coefficient, u/f.
$u = kf$ = monthly consumptive use, inches.

TABLE 46

COMPUTED NORMAL UNIT CONSUMPTIVE USE OF WATER BY ALFALFA, UPPER SALINAS VALLEY, CALIFORNIA

Month	Mean Monthly Temperature, °F (t)	Daytime Hours, % (p)	Consumptive-Use Factor (f)	Coefficient (k)	Consumptive Use, Inches (u)
April	57.9	8.85	5.12	0.60	3.07
May	62.5	9.82	6.14	.70	4.30
June	65.7	9.84	6.46	.80	5.17
July	68.4	10.00	6.84	.85	5.81
August	67.8	9.41	6.38	.85	5.42
September	66.6	8.36	5.57	.85	4.73
October	62.2	7.84	4.88	.70	3.42
Total consumptive use for irrigation season					31.92

$f = \dfrac{t \times p}{100}$ = monthly consumptive-use factor.
k = monthly coefficients developed from observed data on alfalfa in San Fernando Valley.
$u = kf$ = monthly consumptive use.

The consumptive use of water by a particular crop in some area being known, an estimate of the use by the same crop in some other area may be made by application of the formula $U = KF$.

This method was used to compute monthly consumptive use by alfalfa in Salinas Valley, California. Table 46 illustrates the method. Monthly coefficients k were developed from measured consumptive use u and temperature t in San Fernando Valley, California.

229. Integration Method The integration method is the summation of the products of unit consumptive use for each crop times its area,

plus the unit consumptive use of native vegetation times its area, plus water surface evaporation times water surface area, plus evaporation from bare land times its area.

Before this method can be successfully applied it is necessary to know unit consumptive use of water and the areas of various classes

TABLE 47

AREAS OF DIFFERENT CROPS AND CONSUMPTIVE USE OF WATER IN MESILLA VALLEY AREA, NEW MEXICO, AND TEXAS, AS ESTIMATED BY INTEGRATION METHOD, USING DIFFERENT UNITS, 1936 (ISRAELSEN AND BLANEY)

Land Classification	1936 Area, Acres (*a*)	Consumptive Use*	
		Unit, Feet (*c*)	Annual, Acre-Feet (*ca*)
Irrigated crops:			
Alfalfa and clover	17,077	4.0	68,308
Cotton	54,513	2.5	136,282
Native hay and irrigated pasture	216	2.3	497
Miscellaneous crops	11,117	2.0	22,234
Entire irrigated area	82,923	2.74	227,321
Natural vegetation:			
Grass	2,733	2.3	6,286
Brush	6,933	2.5	17,332
Trees-Bosque	3,532	5.0	17,660
Entire area	13,198	3.13	41,278
Miscellaneous:			
Temporarily out of cropping	5,569	1.5	8,354
Towns	1,523	2.0	3,046
Water surfaces, pooled, river, and canals	4,081	4.5	18,364
Bare lands, roads, etc.	3,124	0.7	2,187
Total (entire area)	110,418	2.72	300,550

* *ca* = the product of unit consumptive use in feet (*c*) times area in acres (*a*).

of agricultural crops, native vegetation, bare land, and water surfaces. Unit values of the consumptive use of water by crops can be obtained by some of the methods previously described. By means of aerial maps and field surveys the areas of various types of native vegetative cover and bare land and water surfaces can be determined.

Results of determinations of consumptive use by this method in the Mesilla Valley, New Mexico, and Texas are presented in Table 47.

230. Inflow-Outflow for Large Areas The inflow-outflow method is described in detail in the report of the Upper Rio Grande Basin (1938) and in the report of the Duty of Water Committee, American Society of Civil Engineers (1930). Applying this method, the valley consumptive use U is equal to the water that flows into the valley during a 12-mo. year I, plus the yearly precipitation on the valley floor P, plus the water in ground storage at the beginning of the year G_s, minus

TABLE 48

VALLEY CONSUMPTIVE USE OF WATER AS DETERMINED BY THE INFLOW-OUTFLOW METHOD IN SEVERAL AREAS OF THE WEST

Location	Year	Area, Acres	Annual Consumptive Use		Authority
			Total, Acre-Feet	Unit, Feet	
San Luis Valley, Colo.	1925–1935	400,000	664,900	1.66	Blaney-Rohwer
San Luis Valley, Colo.	1936	400,000	685,423	1.71	Blaney-Rohwer
San Luis Valley, Colo.	1930–1932	17,300	26,215	1.52	Tipton-Hart
Isleta-Belen, N. Mex.	1936	17,500	38,700	2.28	Blaney-Morin
Mesilla Valley, N. Mex.	1919–1935	109,000	297,756	2.73	Israelsen-Blaney
Mesilla Valley, N. Mex.	1936	110,418	303,683	2.75	Israelsen-Blaney
Carlsbad, N. Mex.	1921–1939	51,700	129,752	2.51	Blaney-Morin
Carlsbad, N. Mex.	1940	51,700	119,898	2.33	Blaney-Morin
New Fork, Wyo.	1939–1940	25,000	......	1.50	Lowry-Johnson
Michigan-Illinois, Colo.	1938–1940	43,000	......	1.50	Lowry-Johnson
Uncompahgre, Colo.	1938–1940	137,700	......	2.28	Lowry-Johnson

the water in ground storage at the end of the year G_e, minus the yearly outflow R; all volumes measured in acre-feet; thus

$$U = (I + P) + (G_s - G_e) - R \tag{52}$$

The difference between the storage of capillary water at the beginning of the year and at the end of the year is considered negligible. It is assumed that stream measurements are made on bedrock controls and that the subsurface inflow is about the same as subsurface outflow. The quantity $(G_s - G_e)$ is considered as a unit so that absolute evaluation of either G_s or G_e is unnecessary, only the difference being needed. This is the product of the difference in the average depth of water table in January of one year to January of the following year, measured in feet, and multiplied by the specific yield* of the soil and area of the valley floor. The quantity P is obtained by multiplying the

*The specific yield is defined as the total pore space of the soil less the moisture content at field capacity, both expressed as volume percentages of the total soil volume.

TABLE 49

MEAN ANNUAL OR SEASONAL CONSUMPTIVE USE OF WATER BY NATURAL VEGETATION AS DETERMINED BY TANK AND SOIL MOISTURE STUDIES IN SEVERAL WESTERN STATES

Locality	Type Vegetation	Period of Record (Inclusive)	Depth to Water Table, In.	Consumptive Use, In.	Evaporation,* In.	Precipitation, In.	Authority
Arizona							
Safford	Tamarisk	May–Dec. 1940	24	61.1	53.1	.....	Turner and Halpenny
Safford	Tamarisk	May–Dec. 1940	48	47.9	53.1	.....	Turner and Halpenny
Safford	Baccharis	May–Dec. 1940	24	52.0	53.1	.....	Turner and Halpenny
Safford	Baccharis	May–Dec. 1940	48	39.7	53.1	.....	Turner and Halpenny
California							
Santa Ana	Salt grass	May, 1929–Apr. 1932†	24	35.3	66.6	12.29	Blaney and Young
Santa Ana	Salt grass	May, 1929–Apr. 1932†	48	13.4	66.6	12.29	Blaney and Young
Santa Ana	Wire rush	Aug. 1930–July, 1931	24	78.9	67.6	11.11	Blaney and Young
San Bernardino	Bermuda grass	May, 1929–Apr. 1931†	24	34.4	66.5	13.02	Blaney and Young
San Bernardino	Brush	Oct. 1927–Sept. 1930†	‡	21.6	65.0	25.91	Blaney and Taylor
San Bernardino	Grass-weeds	Oct. 1928–Sept. 1929	‡	10.0	....	10.75	Blaney and Taylor
Ontario	Grass-weeds	Oct. 1927–Sept. 1928	‡	13.4	....	13.40	Blaney and Taylor
Claremont	Brush	Oct. 1927–Sept. 1930†	‡	14.6	....	14.65	Blaney and Taylor
Victorville	Tules	Jan. 1931–Dec. 1932	0	78.4	82.5	9.02	Blaney and Taylor
King Island	Tules	Jan.–Dec. 1932	0	90.0	....	.....	Stout
San Luis Rey	Cottonwood-willows	Apr. 1941–Mar. 1943†	48	62.5	57.8	.....	Blaney and Muckel
Owens Valley	Salt grass	Jan.–Dec. 1911	46	24.6	....	5.56	Lee

Idaho						
Grays Lake	Wild hay	June 22–Sept. 30, 1942–1944	18	31.2	26.5	2.37 Criddle and Marr
Grays Lake	Tules	June 22–Sept. 30, 1942–1944	0	42.4	26.5	2.37 Criddle and Marr
Bonner's Ferry	Cattails	May–Sept. 1934–1944	0	61.6	33.5	5.06 Criddle and Marr
Bonner's Ferry	Canadian thistle	May–Sept. 1934–1944	30	34.1	33.5	5.06 Criddle and Marr
Colorado						
San Luis Valley	Meadow grass	June–Nov. 1936	0	36.3	30.8	7.13 Blaney
San Luis Valley	Tules	June–Nov. 1936	0	38.8	30.8	7.13 Blaney
Ft. Collins	Sedge grass	May–Oct. 1930	18	53.6	....	..... Parshall
Ft. Collins	Rushes	July–Oct. 1930	..	52.6	....	..... Parshall
New Mexico						
Los Griegos	Salt grass	Oct. 1927–Sept. 1928	26	22.7	77.6	7.03 Elder
Isleta	Salt grass	June, 1936–May, 1937	8	31.6	....	10.89 Blaney
Isleta	Sedge grass	June, 1936–May, 1937	3	76.9	....	10.89 Blaney
Carlsbad	Tamarisk	Jan.–Dec. 1940	36	57.3	92.6	12.84 Blaney
Carlsbad	Sacaton	Jan.–Dec. 1940	36	44.8	92.6	12.84 Blaney
State College	Cattails	July–Dec. 1936	0	44.2	36.5	..... Blaney
State College	Salt grass	July–Dec. 1936	14	29.3	36.5	..... Blaney
Utah						
Escalante Valley	Salt grass	May–Oct. 1927	23	22.6	72.6	4.47 White
Escalante Valley	Greasewood	May–Oct. 1927	26	25.2	72.6	4.47 White

* Evaporation from standard Weather Bureau pan.
† Average yearly for period of record.
‡ Determined by soil sampling to 17 ft. Water table below 100 ft.

average annual precipitation in feet by the area of the valley floor in acres. The unit consumptive use of the entire valley in acre-feet per acre is obtained by dividing the total consumptive use by the area of the valley floor.

Results of typical inflow-outflow measurements in several areas are given in Table 48.

231. Consumptive Use by Natural Vegetation The water consumed by natural vegetation usually cannot be made available for other important purposes. In considering the water supply of a region, water consumed by natural vegetation, such as salt grass, willows, cottonwoods, tamarisk, and tules growing in irrigated valleys, moist areas, and along streams becomes of increasing importance as greater land areas are irrigated, especially during periods of drought. The value of data on consumptive use by these non-crop plants is recognized by administrators and engineers in regions where water rights are in dispute, or where interstate water supply and water use are not in balance. In planning new irrigation projects consideration must often be given to differences in consumptive uses of water utilized by irrigated crops and by the natural vegetation replaced by the crops.

The relation of plant communities to moisture supply is one of the outstanding characteristics of the growth of natural vegetation. Whereas individual species are largely restricted to physical environments, the principal condition that governs distribution of vegetative groups is the available water. Each species responds to water conditions for its most favorable growth and its widest distribution. Temperatures, moisture, and the chemical and physical properties of the soils are contributing factors in the distribution of natural vegetation. The quantity of water available for plant use and the effect of plant growth on supply are of great interest to irrigation engineers and hydrologists.

Consumptive use by natural vegetation growing in areas of high water table is measured by means of tanks or lysimeters. The unit values thus determined are used to compute valley consumptive use by the integration method previously described. Results of typical studies are presented in Table 49.

Measurements of consumptive use indicate that water-loving natural vegetation uses from 50 to 100 percent more water than most crop plants. Tules and cattails growing in and near irrigation canals and drainage ditches are exposed in narrow strips to sun and wind so that their consumption of water is high. Under such circumstances the natural vegetation along a mile of canal or ditch may consume enough water to irrigate 8 or 10 acres of alfalfa or a greater acreage of other field crops or of fruit.

15
Irrigation of Cereals, Forage, and Root Crops

Irrigation practices are determined largely by three conditions, namely: the climate of the locality, the soils under cultivation, and the crops grown. The depth of water properly applied in a single irrigation, the size of stream used, the length and width of land covered with a given stream, and the frequency of irrigation—all these factors are influenced by the land topography and soil conditions, but they are influenced also to some extent by the crops grown. The method of irrigation selected, whether by flooding, in furrows, or corrugations, or by sprinkling, is based on the type of soil, land topography, and the crop produced.

Wheat, oats, barley, rye, and corn, the major cereals, are grown both under dry farming and irrigation.

232. Irrigating Cereals Cereals are irrigated by ordinary flooding, border-strip flooding, corrugation, and furrow methods. The check or basin method of flooding is also used on highly permeable soils.

Grain crops are rarely grown continuously from year to year on any one tract of irrigated land; rather they form a part of a crop rotation. On new irrigation projects grains sometimes form the major crop, but experience has demonstrated the desirability of producing forage and other crops as soon as the new lands can be properly prepared. The method of irrigation selected for small grains is influenced by the methods utilized for other crops in the rotation period. If the land has been prepared for irrigation of alfalfa by the border-strip method, grains are irrigated by the same method. Likewise, if it is customary to irrigate the alfalfa by the corrugation method, the farmer may well apply the same method for irrigating grain.

Where water is plentiful, especially during the early part of the season when grains are irrigated, the ordinary flooding method predominates. Where the water supply is limited and expensive the corrugation method or the border method is used.

In the intermountain states with deep loam soils the grains can be matured by the irrigation water applied in May and June, the months of flood discharges of the streams. On shallow soils, having low capacities for available water, irrigation of cereals is essential also in July.

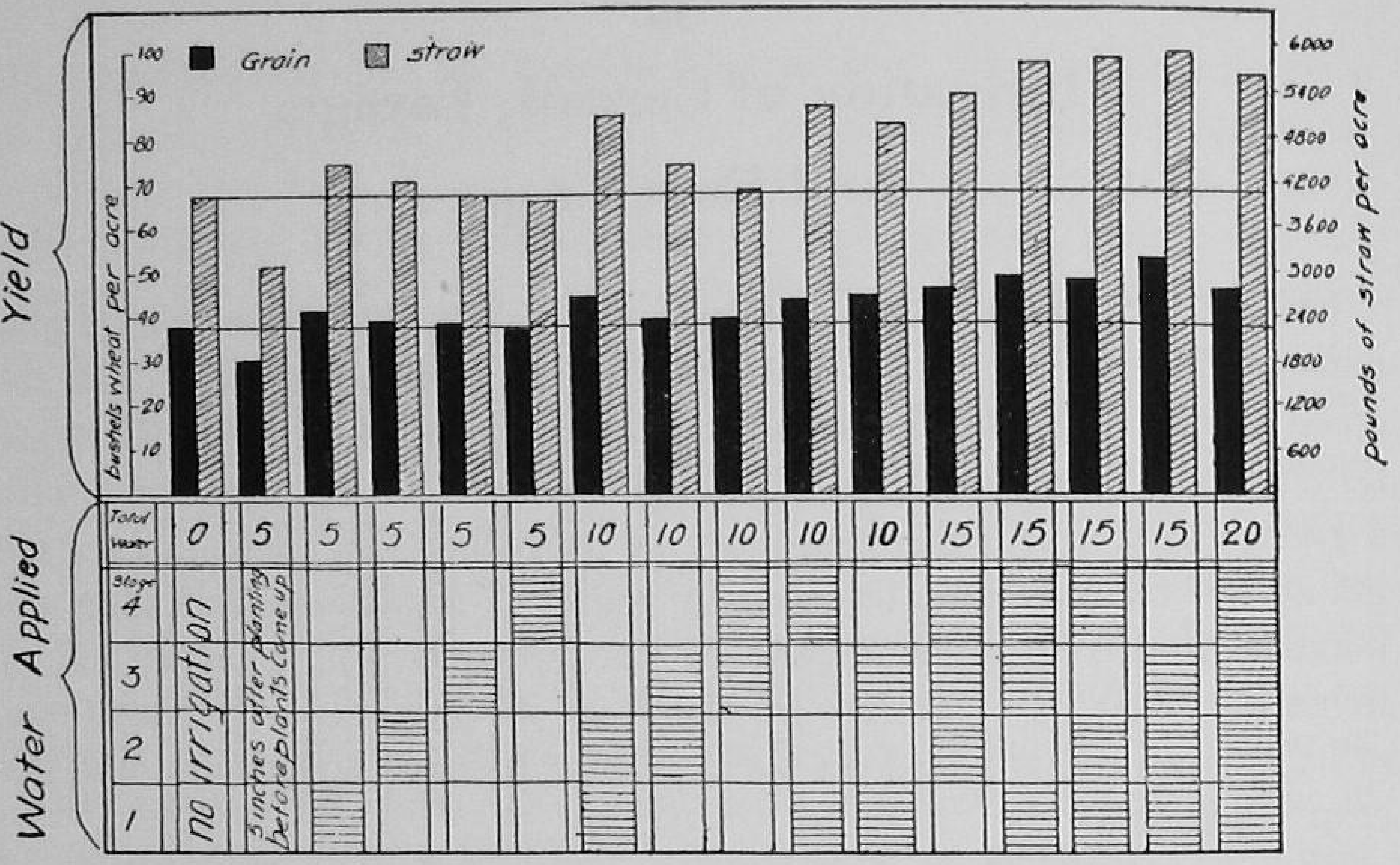

FIG. 159. Yield of wheat grain and straw on plots receiving various quantities of irrigation water at different stages. (*Utah Agr. Exp. Sta. Bul.* 146.)

Experiments at the Utah Station show advantages in irrigating cereals at certain stages of their growth. Harris irrigated wheat plots just after planting and at four stages as follows:

1. The stage when fine leaves have developed and the plants are 6 to 8 in. high.
2. The early boot stage when the plants were just swelling preparatory to heading.
3. The bloom stage when most of the plants were in bloom.
4. The dough stage when most of the plants were in the dough.

The soils of the experimental farm are deep loams of comparatively uniform texture, retentive of moisture, and highly productive when properly managed. The results of 4 years' work are presented in Fig. 159. In the lower half, the shaded areas show the stages at which water was applied, and the upper half shows in black columns the yield of grain and in shaded columns the yields of straw. The numbers from the reader's left to right show the total amounts of irrigation water given to each crop. The plot which received no irrigation water

produced approximately 38 bu of grain with the moisture stored in the soil from the winter snow together with the water received from rainfall during the crop-growing season. The mean total annual precipitation during the 4-yr period was 17.8 in. The plot that was given a 5-in. irrigation before the plants came up produced less than any of the plots which were given a 5-in. irrigation in each of the

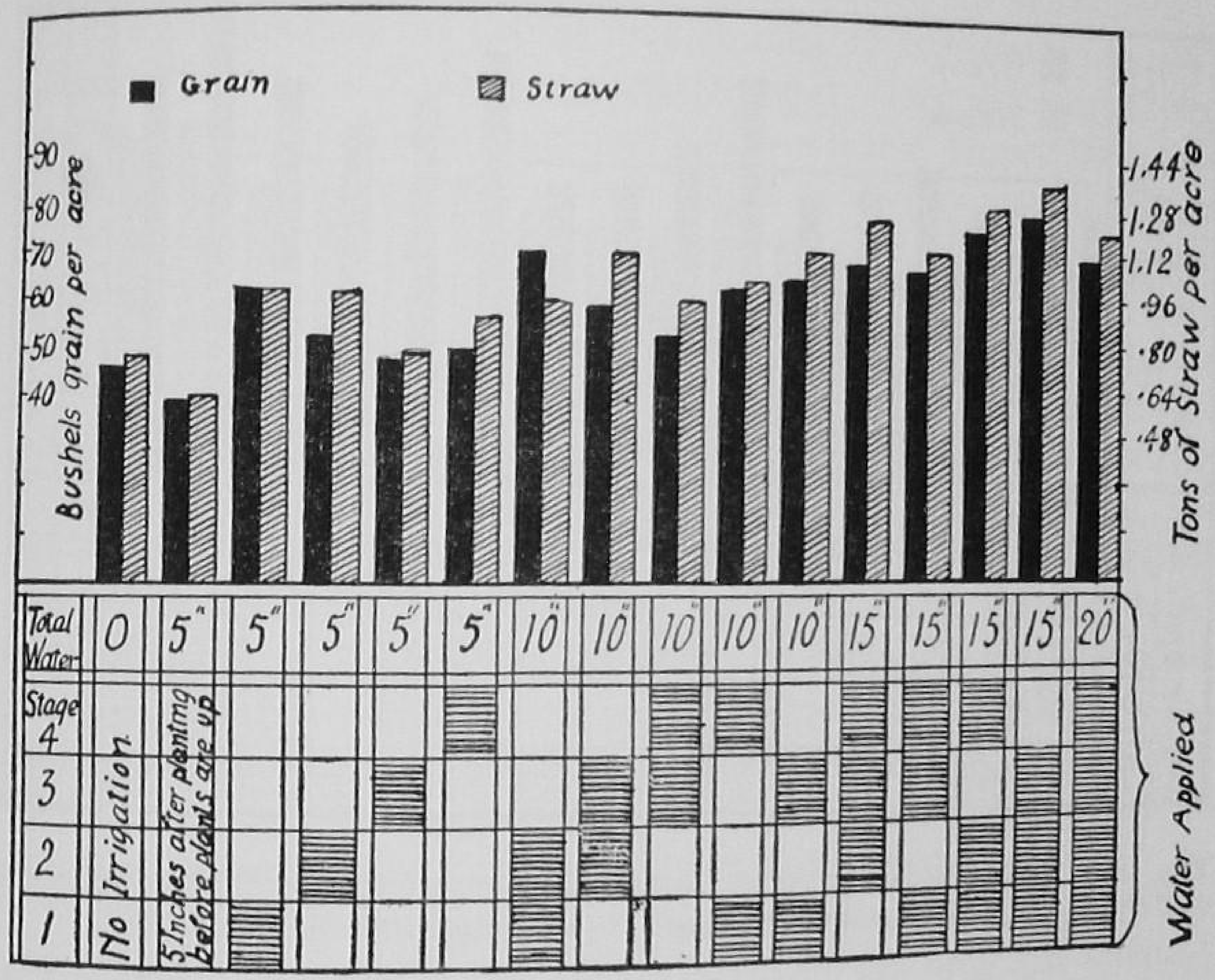

FIG. 160. Yield of oat grain and straw on plots receiving various quantities of irrigation water at different stages. (*Utah Agr. Exp. Sta. Bul.* 167.)

four stages above described and also less than the plot that received no irrigation water. The figure shows the advantages of irrigation during the earlier stages for the 5-in., the 10-in., and the 15-in. total seasonal applications. It is also significant that the 15 in. of water applied on each of the first three stages produced more wheat than 20 in. when applied in four 5-in. irrigations.

Three years' experimental work at the Utah Station on the irrigation of oats is reported in Fig. 160, which reveals the importance of early irrigation.

During the three years, 1919 to 1921, Harris and Pittman conducted experiments on the irrigation of barley similar to the experiments for wheat and oats. The results of the barley irrigation experiments are shown in Fig. 161.

After several years' study of the production of grains at the Aberdeen substation, Idaho, Aicher concluded that set rules for the irrigation of any crop are misleading and impractical. Seasons vary, and the time to irrigate a crop varies considerably with the season. Summer rains often are misleading unless they exceed ½ in. In southern Idaho, where the average precipitation during the growing season is 4.27 in.,

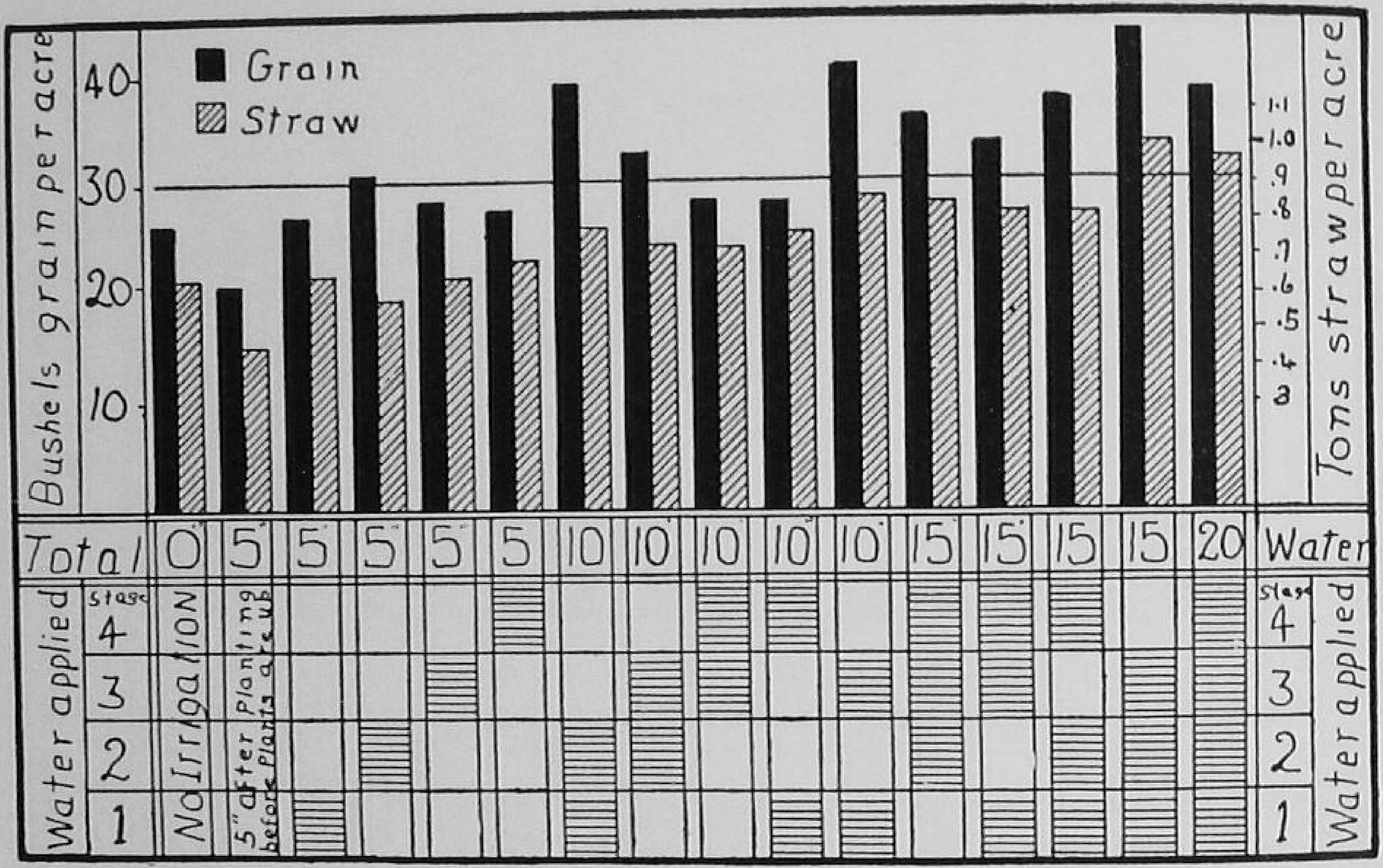

FIG. 161. Yield of barley grain and straw on plots receiving various quantities of irrigation water at different stages. (*Utah Agr. Exp. Sta. Bul.* 178.)

it is a mistake to take the average shower too seriously. The immediate surface moisture is of little value in crop production, and unless the ground is moist to a considerable depth the crop should be irrigated regardless of the moisture added by small rains.

233. Water Requirements of Cereals The data presented in Fig. 161 indicate that a seasonal depth of 15 in. of water, applied in the first three stages in three 5-in. irrigations to deep retentive soils, produced more barley than one 20-in. or four 5-in. applications.

From experiments on the irrigation of spring wheat grown on the medium clay loam soil of the Gooding substation, Idaho, it was concluded that 15 in. net was a sufficient depth for spring wheats and approximately 8 in. for winter wheats. The average annual rainfall at the Gooding substation during the period of experiment was 9.2 in., of which 2.9 in. came during the crop-growing season, April 1 to August 31.

In Nevada, the highest yield of wheat was obtained with a depth of 28 in. of water. The soils of the Experiment Station Farm vary from sandy loams to clay loams, and have an average depth of 4 ft, below which there is a coarse sand and gravel. The average annual rainfall during the 5-yr period was less than 8 in., and during the crop-growing season the rainfall was negligible.

In the Salt River Valley, Arizona, Marr studied the water needs of wheat by measuring the depths used on some 15 farms under ordinary practice. The soil of 7 farms is classed as sandy loam, of 1 as loam, and of 7 as clay loam. The annual precipitation is low. During the period of the observations it ranged from 4.5 in. to slightly more than 9 in. Marr concludes that 17 to 22 in. of water is sufficient to mature wheat and similar crops in the Salt River Valley.

In the Mesilla Valley, New Mexico, the average annual precipitation is from 8 to 9 in., of which an average of 5.8 in. falls during the summer season. The summer rains come in small showers, the average being 0.3 in. in 24 hr. The evaporation following rains is rapid, and the depth of penetration of rains into the soil is shallow. The influence of natural precipitation during the crop-growing season is negligible as a source of water. On the basis of a study of wheat production on 28 farms that received depths of water ranging from 7 to 25 in., Bloodgood and Curry concluded that fields receiving about 19 in. of water per season, applied in approximately 4-in. depths with an irrigation season of 150 days, gave the most satisfactory yields.

Fortier and Young have made a careful study of the irrigation requirements and the water requirements of the arid and semiarid lands of the Southwest, from which they conclude that the water requirements of wheat, which include irrigation water, stored soil moisture, and seasonal rainfall, range from 17.5 in. as the lowest general average to 27.0 in. as the highest general average.

The depths of water needed to produce oats differ but little from the depths needed for wheat. Harris and Pittman found that excellent yields of oats could be produced with only 15 in. of irrigation water applied at the proper time. For conditions like those of the Gooding substation, Idaho, Welch recommends about 21 in. of water for oats. Beckett and Huberty report that in the Sacramento Valley, California, during years of average or high rainfall, oats can be profitably produced without irrigation, whereas during years of low rainfall two average irrigations will bring profitable returns through increased yield of oats. Under favorable soil conditions in the intermountain states, where the annual precipitation is 18 in. or more, oats may be produced without irrigation.

Barley requires but moderate depths of irrigation water. Harris and Pittman found, as shown in Fig. 161, that only 10 in. applied during the early stages of growth produced 40 bu per acre, whereas 15 in. applied in three irrigations, one irrigation in each of the first three stages, produced approximately 42 bu which was nearly 4 bu more than was produced by 20 in. of irrigation water. For Snake River Valley conditions similar to those at Gooding, Welch recommends 18 in. for spring barleys.

Widtsoe found that maximum corn yields of nearly 100 bu of grain per acre were produced at the central Utah Station with 25 in. of irrigation water. His experiments also gave excellent yields with only 10 to 15 in., and he concluded that under favorable soil conditions and in a climate such as prevails in Cache Valley, Utah, 12 to 15 in. of water is satisfactory for corn.

Pittman and Stewart show that under the conditions of the Utah Central Experiment Station Farm corn increases in yield with increase in irrigation water up to about 20 in.; that the yields change but little as the water is increased from 20 to 30 in., above which there is a decrease. With an adequate supply of water on fertile soils, the corn crop will yield from 60 to 80 bu of grain per acre, or from 17 to 20 or more tons of silage.

234. Irrigating Alfalfa Two-thirds of the acreage devoted to alfalfa in the United States is in the 17 western states, largely under irrigation. The irrigation methods most common for alfalfa are flooding from field ditches, border flooding, and check or basin flooding. In localities where water supplies are limited and where land surfaces are not suitable to border flooding or basin flooding, alfalfa is irrigated by the corrugation method. In alfalfa-seed-producing areas the corrugation method is especially advantageous because it permits more thorough cultivation for control of insect pests.

Temporary submergence of alfalfa lands that are irrigated by the flooding method is not harmful, but submergence for many hours proves very harmful at times. High temperatures and reflection of the sun's rays from water surface to young alfalfa plants is injurious. Long periods of submergence during the warmer parts of the season should be avoided. For alfalfa on soils having low infiltration rates it is good practice to irrigate frequently and apply small depths of water at each irrigation. For soils having low infiltration rates the furrow or corrugation method is advantageous. Small streams may be kept in the furrows for longer periods and thus increase infiltration of water without endangering the plants and also without wetting and puddling the entire soil surface.

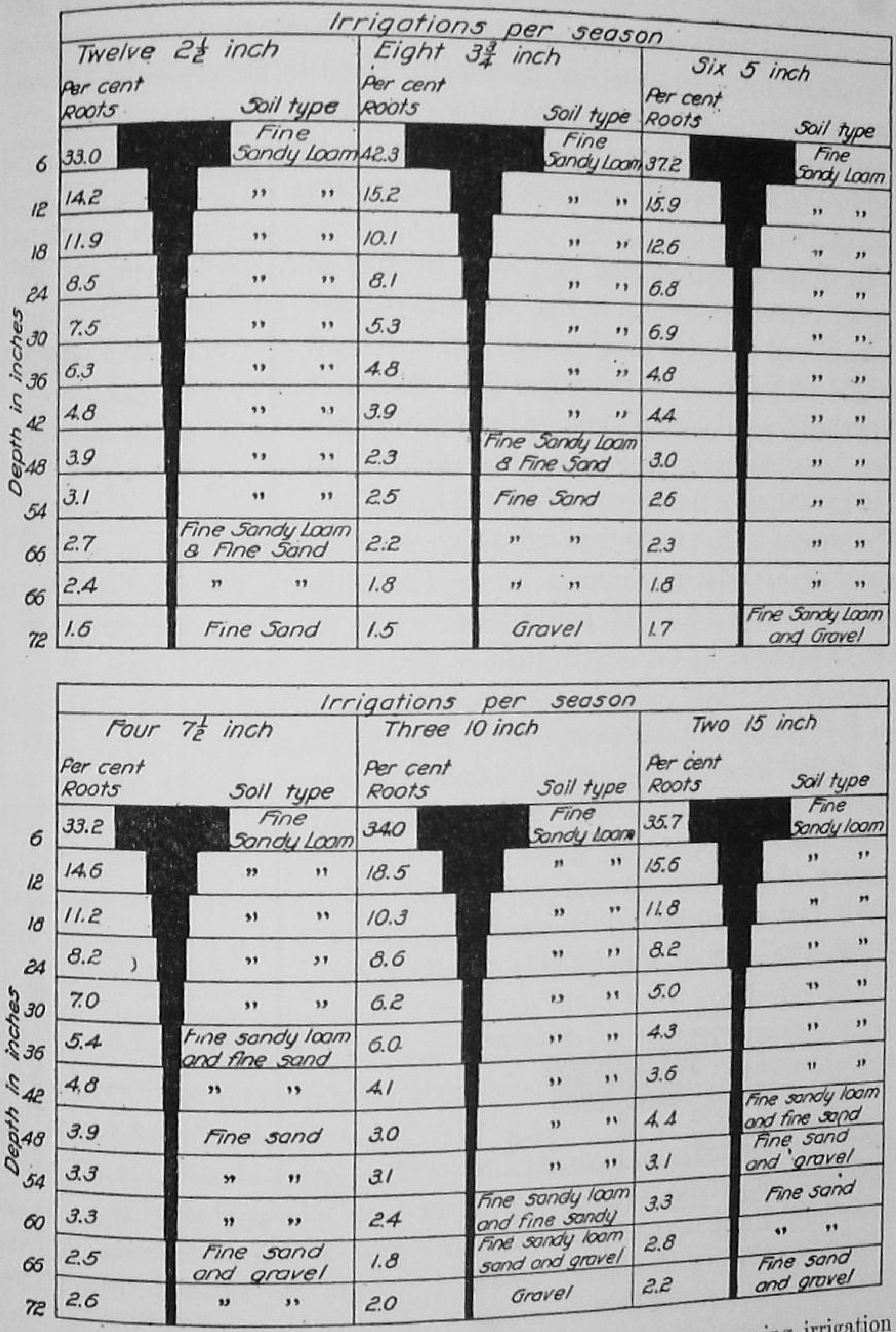

FIG. 162. Diagram showing root distribution of alfalfa under varying irrigation treatments at University Farm, Davis, California. Note that the root distribution has apparently not been affected by variation in irrigation treatments. (*Calif. Agr. Exp. Sta. Bul.* 450.)

Alfalfa and pasture lands permit the use of larger streams than can be handled for grains or root crops. On lands that are properly prepared for irrigation by the border or the check method streams of 5 to 10 cfs are used in irrigating alfalfa. Even larger streams are used for alfalfa irrigation in parts of California. The basin method for the irrigation of alfalfa is applied to some extent where the land slopes are not excessive.

In spite of deep rooting of alfalfa in soils of open structure, as shown in Fig. 162, the surface 6 in. of soil had one-third or more of the total weight of the roots in the upper 6 ft. Water is absorbed from the soil by plants largely through the tiny root hairs, which are most difficult to find in making a field study of root distribution. The weight of the roots through which water is absorbed is relatively small. It is therefore significant that 1.5 to 2.6 percent by weight of the total roots in the upper 6 ft of soil were found in the ½-ft section immediately above the 6-ft depth. Alfalfa plants probably obtain the major water supply and nutrients in the upper few feet of soil, but in well-drained soils some roots penetrate to great depths where changes of moisture content of the soil occur slowly and where the total extent of variation of moisture is small. The roots of alfalfa grown in soils having a shallow water table are largely concentrated near the surface. Figure 163 illustrates how a water table at 3 ft caused a growth of more than 97 percent of the roots in the upper 2 ft of soil. Poorly drained alfalfa soils are first to permit serious damage to the plants through drought. The hot summer days and dry atmosphere cause

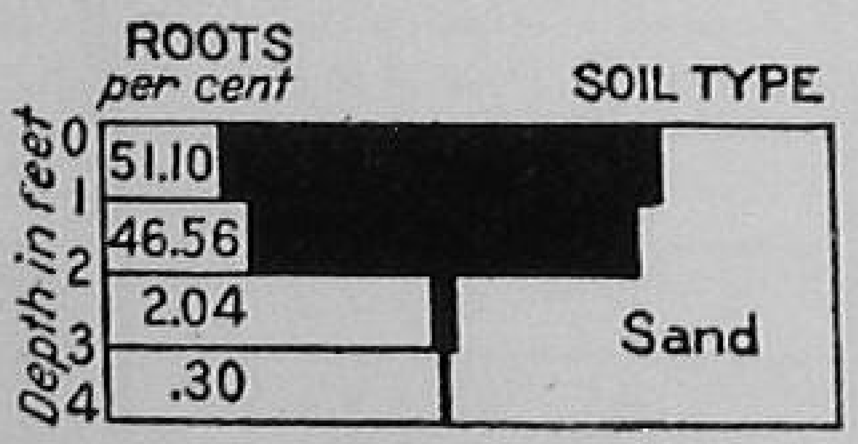

FIG. 163. Distribution of alfalfa roots with a water table 3 ft below ground surface.

Depth, ft	Water used: Inches per year	Water used: % of total
0-1	6.8	13
1-2	7.2	14
2-3	7.3	14
3-4	6.7	13
4-5	5.6	11
5-6	4.7	9
6-7	4.0	8
7-8	3.5	7
8-9	2.8	6
9-10	2.3	5

FIG. 164. Use of water by alfalfa in Arizona from each foot of the root-zone soil.

rapid loss of water from the surface soil by transpiration and evaporation, the water table lowers, and the shallow soil zone in which roots are distributed has not enough stored water to meet the needs of the plants, with the result that drought damage is noticeable early.

The University of Arizona studies reported in Fig. 164 show 65 percent of the water withdrawn by the alfalfa from the soil was taken from the upper 5 ft, and 35 percent from the depth 6 to 10 ft. The maximum withdrawal was from the second and third foot sections which together provided 14.5 in. of water to the alfalfa, more than one-fourth of the total of nearly 51 in.

Growth of alfalfa in a given soil is influenced largely by two factors, namely: (*a*) the available heat, and (*b*) the readily available water supply. In irrigation farming, man can provide adequate available soil moisture to assure maximum rate of growth that the available heat will permit.

Alfalfa growers can detect from the appearance of the leaves of the growing alfalfa the time that irrigation water is needed. A dark green color is usually evidence of the need for water. Temporary wilting is warning that the supply of soil moisture is near exhaustion. Where water is delivered by the rotation method, the irrigator must determine shortly before each water turn whether to irrigate within a day or two or wait the coming of the second water turn, possibly 10 to 15 days later. Boring into the soil to a depth of 5 or 6 ft with a soil auger and examining the soil moisture condition is a very helpful aid to judgment in determining the time to irrigate. There should be no dry soil in the upper 6 to 8 ft during the alfalfa-growing season.

Because of the many variable influencing factors there can be no definite frequency period of irrigation of alfalfa applicable to all conditions. The factors of major influence are the texture and depth of the soil; the temperature, atmospheric humidity, and winds; and the crop-season rainfall.

On sandy soils it may be best to irrigate every 2 weeks, whereas on the sandy loam soils on which two or three alfalfa cuttings are secured two irrigations per cutting may be best; on the heavy deep soils one irrigation per cutting is adequate. For the shallow, coarse-textured soils, irrigation every 10 days during the warmer part of the season is common; and light irrigations once a week are not exceptional on gravelly shallow soils. Many of the alfalfa tracts on deep loam soils produce abundantly when given one irrigation about 1 week before cutting the first crop, one shortly after harvesting the first crop, one before cutting the second crop, and one about 2 weeks after cutting the second crop.

235. Water Requirements of Alfalfa As compared to most of the crops grown under irrigation, alfalfa requires large depths of irrigation water because of the large annual tonnage production. Grain crops mature in time periods ranging from 90 to 110 days, whereas alfalfa, adequately irrigated, grows continuously as long as the mean temperatures are well above the minimum growing temperature. The longer the growing season, the greater the irrigation requirement for alfalfa and the greater the tonnage produced. The growing season for alfalfa ranges from less than 100 days annually in high northern valleys to more than 300 days in low valleys of Arizona and California. The annual yield of alfalfa varies from less than 4 tons per acre to more than 10 tons, according to climatic and soil conditions and length of growing season.

Adams and others have made extensive studies of the irrigation requirements of alfalfa in California. At the University Farm, at Davis, California, they found a maximum alfalfa yield with 36 in. of irrigation water and concluded that the most economical depth of irrigation water for alfalfa at Davis ranges from 30 to 36 in. The results of their work are presented in Fig. 165.

236. Clover Crops Under Irrigation Several different varieties of clover are produced under irrigation both for pasture and for hay. Large amounts of clover seed also are produced under irrigation.

Under the same climatic and soil conditions as for alfalfa, the clover crops thrive best with more frequent irrigation than alfalfa requires. Small depths of water at each irrigation will meet the needs of the clover crops so that during the entire growing season they require no more water than alfalfa and probably a little less.

237. Grasses Under Irrigation Timothy, orchard grass, brome grass, and other hay-making grasses thrive in irrigated regions. Timothy and the native grasses live in spite of excessive irrigation and frequent submergence, but moderate depths of water are best suited to their needs. Low-lying land areas are often relatively wet on account of seepage from higher lands and inadequate natural drainage. Such lands produce one cutting for hay annually, the yield ranging from 1.0 to 1.5 tons per acre, after which a good growth of fall pasture is produced. Low lands that are excessively wet during the early spring and late fall are not suitable to the growth of alfalfa. When effective artificial drainage is provided for lands which ordinarily grow only timothy and native grasses they produce alfalfa abundantly. Powers and Johnston, in a study of irrigation requirements of wild meadow and hay land in Oregon, found it practical to produce on reclaimed tule land a

yield of clover and timothy of 3½ tons per acre, which is more than 3 times the average yield of wild hay.

There are large areas of irrigated grass lands that may yield much higher returns through drainage, followed by planting clovers or alfalfa.

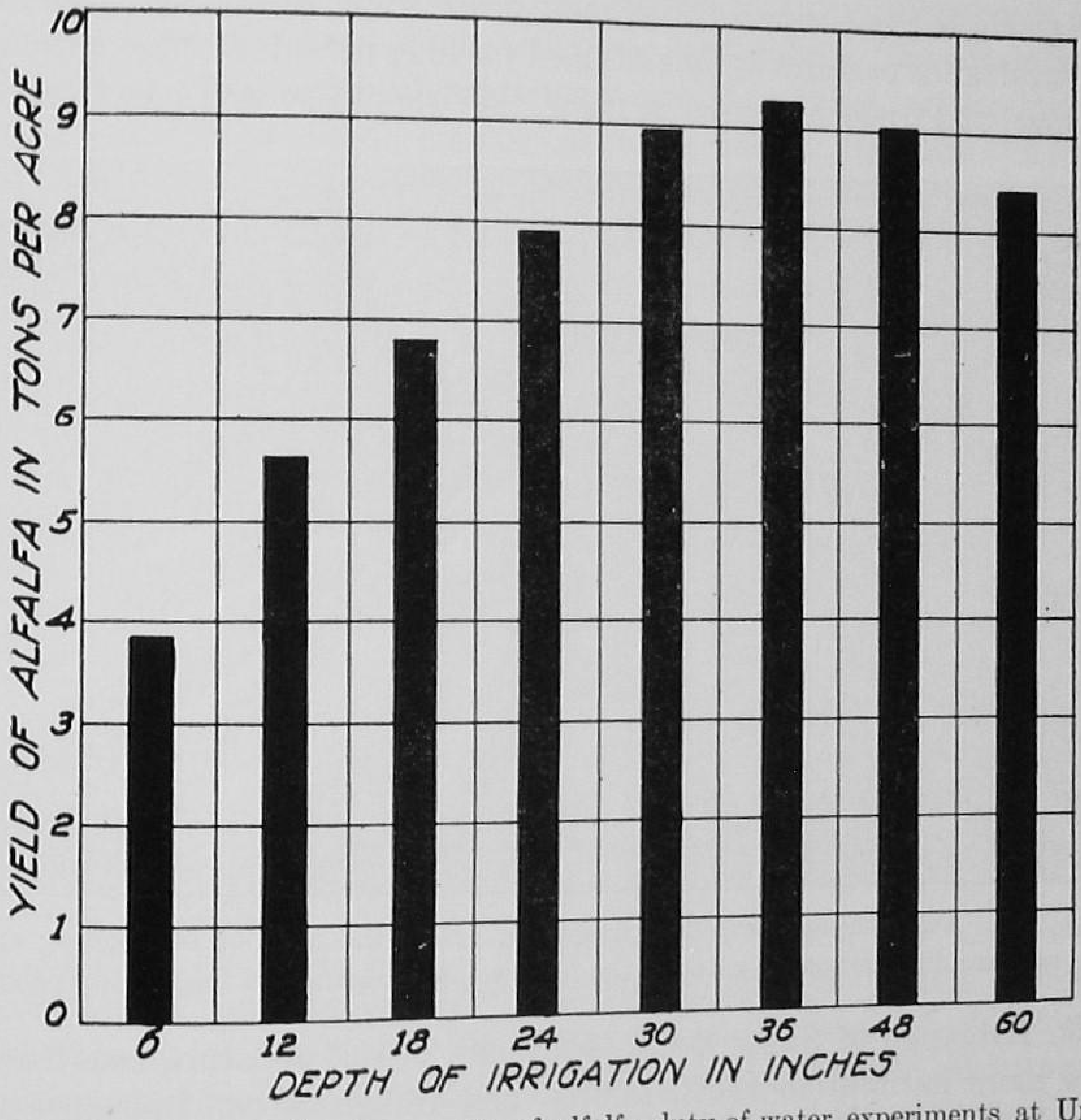

FIG. 165. Diagram showing results of alfalfa duty-of-water experiments at University Farm, Davis, California, 1910–1915. Under the conditions present, the most economical yields were obtained with annual applications of 30 to 36 in. (*Calif. Agr. Exp. Sta. Bul.* 450.)

238. Irrigated Pastures Pastures of perennial grasses and legumes, such as Ladino clover, or alfalfa, are irrigated by flooding from field ditches, border flooding, check or basin flooding, contour check, and often by sprinkling. Less frequent cultivation of pasture lands results in lower yearly cost of preparation of land. Soils producing pastures are not as subject to erosion as soils with crops.

Under the same climatic and soil conditions as for alfalfa, pastures thrive best with more frequent irrigations. Roots of pasture plants are near the soil surface as compared to alfalfa roots. The resulting

shallower plant-feeding zone requires more frequent applications of water.

A common practice among irrigation farmers is to irrigate pastures at night when it is more difficult to irrigate annual crops. If the irrigation structures utilized for pastures are properly placed the work of irrigating is less compared with most other crops. Since the irrigation structures for pastures are maintained for long periods of time without change, and frequently used at night, they should be well constructed.

FIG. 166. An example of excellent irrigation. Note the absence of flooding and the uniform distribution of water in the furrow. (Amalgamated Sugar Company.)

239. Irrigation of Sugar Beets Extremes in soil moisture conditions are more harmful to beets, alfalfa, and forage crops. Improper or careless handling of water on beet land, especially early in the season, causes soil erosion, puddling, cracking, baking, etc., all of which are seriously detrimental to beet production.

The urgent need for care and for following intelligent approved practices in the irrigation of sugar beets is recognized by sugar company officials, and active educational campaigns are conducted among beet growers as a means of attaining efficient and satisfactory irrigation.

It is common practice to irrigate beets by the furrow or corrugation method as illustrated in Fig. 166. Fine-textured loam and clay loam soils are best suited to the growing of sugar beets, and when irrigated by flooding these soils crack and bake around the young plants and retard growth. Injury results also from contact between water and young beets. Flooding sugar beets is rarely practiced.

Sugar-beet irrigators try to distribute water as uniformly as possible to avoid waste of water and crop injury due to over-irrigation on one part of the land and insufficient depth of penetration of water on another part.

Smoothness of land surface, moderate lengths of carefully made furrows, and proper control of the quantity of water delivered to the furrows from the head ditch—all these contribute to the attainment of uniform distribution of irrigation water. Smoothing and leveling of the surface must be accomplished before seeding the crop. Careful plowing, harrowing, and dragging are essential to satisfactory irrigation of beets. The furrows on open, porous soil should seldom exceed 330 ft, whereas on the loams and clays it is quite customary to have furrows 660 ft long. To assure reasonable uniformity of distribution of water the irrigator must pay particular attention to regulating the size of stream that flows into each furrow. Streams that are too large cause breaking of the furrows and consequent accumulations of the streams from any furrows into one very large stream that damages the soil by erosion and injures the beets. It is impracticable to set precise limits as to the proper size of stream for each furrow, but, in general, the stream in each furrow varies from $\frac{1}{25}$ to $\frac{1}{50}$ cfs. Thus a stream of 1 cfs is made to flow into 25 to 50 furrows at one time. Many beet growers regulate the quantity of water flowing into each furrow entirely by making frequent adjustments in small V-shaped earth outlet ditches. Some place small bunches of grass in the outlet ditches to prevent high velocities and soil erosion. Sometimes one outlet from the head ditch is made to supply from 4 to 8 furrows by subdividing the stream below the head-ditch outlet. More uniform distribution of water may be attained, and the labor of attendance somewhat decreased, by means of small cylindrical metal outlet pipes having a diameter of 1 to 2 in. and lengths of 18 to 30 in. Outlet pipes of this kind are especially desirable where irrigation water is limited and costly. The major objection to them is that they become damaged during times of cultivating the beet fields.

The most general practice is to space the rows uniformly about 20 in. apart and to make furrows between each two rows. For the second irrigation, in which a relatively small depth of water is used, it is quite customary to run the water in alternate furrows that were left dry during the first irrigation. During the periods between the later applications the beets need relatively large amounts of water, and farmers moisten the soil more fully by running the water in all the furrows.

A comparatively new practice that appears to be growing in favor is

to plant the beets in rows differently spaced. For example, the distance between two rows may be but 16 in. whereas the distance between the next two is 24 in. Furrows for irrigation are then made only in the 24-in. open space, thus leaving 40 in. from center to center of the irrigation furrow. Under favorable soil conditions this method is satisfactory and doubtless is saving of water. Heavy compact soils, in which capillary movement of water is very slow, are not well suited to differently spaced alternate-row irrigation practice.

In time of irrigation beets differ from the small grains in the fact that they require large amounts of late-season water. July, August, and September are the months of maximum irrigation needs of beets in the Great Basin beet-growing areas. Because the natural discharge of many streams decreases markedly late in June or early in July it is essential to provide late-season water for beets by storage or pumping.

In the earlier years of beet growing the belief was rather widely entertained that the first irrigation of each season should be delayed until the beets showed definite wilting and consequent urgent need for water: the "struggle for water" thus imposed on the beet stimulated deep rooting, and beets of greater length than would be developed by early irrigation would result. A more recent, and apparently a more rational, basic guiding principle as to time of irrigation of beets is that large yields are more easily produced by providing all conditions, soil moisture included, favorable to a continuous growth of the plants from germination to maturity, at the maximum rate that the temperature conditions will support. The deep loam and clay loam soils in parts of the Rocky Mountain states sugar-beet areas are well supplied with moisture after normal winter snowfall and spring rains. Sugar beets consume water at a low rate during the early part of their growth in May and June. The moisture stored from natural precipitation is usually sufficient during these months to support the maximum possible rate of growth. Beets therefore need relatively late-season irrigation water. In valleys in which both irrigated grains and sugar beets are grown the major irrigation needs of the grain crops are completed before the heavier demands for water by the sugar beets occur.

240. Water Requirements of Beets The seasonal depths of irrigation water required for profitable production of sugar beets are slightly greater than required for small grains but appreciably less than required for alfalfa, especially in climates where the growing season is long.

Results of 10 years' study of the irrigation requirements of sugar

beets are presented in Fig. 167. The half of the figure on the reader's left shows that a maximum yield of more than 20 tons per acre was produced with ten 2½-in. irrigations applied weekly. Ten 1-in. irrigations produced nearly maximum yield and ten 5-in. irrigations produced a smaller tonnage.

Knight and Hardman in Nevada found comparatively small differences in sugar-beet yields as the depth of irrigation water was increased from 12 to 18 and finally to 24 in. The maximum yield was obtained with 18 in.

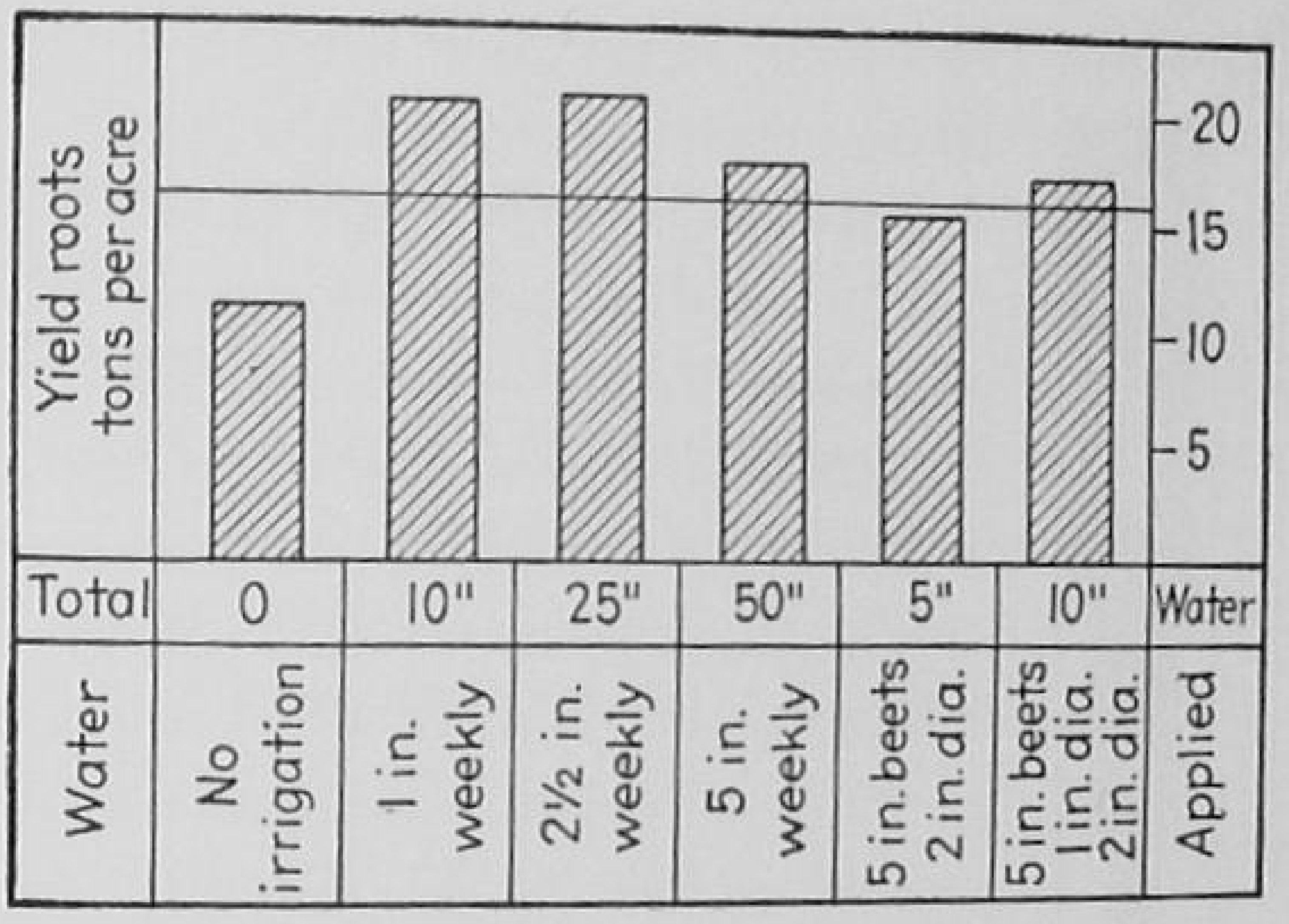

FIG. 167. Yield of sugar beets on plots receiving different irrigation treatments. Average of 10 yr. (*Utah Agr. Exp. Sta. Bul.* 186.)

241. Irrigating Potatoes Reasonable care in smoothing and leveling potato land is essential to satisfactory irrigation. Except under very favorable natural soil conditions that permit sub-irrigation, potatoes are usually irrigated by the furrow method. It is important to avoid direct contact of water with plants, and hence deep furrows are best suited to potato irrigation. Complete saturation of the soil around the potato vines followed by baking and cracking is detrimental to potato production. It is desirable to have the furrows from 10 to 12 in. deep in moist soils, thus eliminating the risk of submerging the vines or of excess water around the tubers. Under favorable topographic and soil conditions potato furrows may be longer than beet furrows. Probably 1320 ft is the maximum profitable length, and as a rule 660 ft is preferable. Shorter furrows are necessary in highly permeable soils.

The basic guide in time to irrigate is the moisture content of the soil. Before potatoes are planted it is important that the soil be well supplied with moisture in order to give the crop a good start before the first irrigation after planting. Where the winter-season

precipitation is too small to fill the soil to its field moisture capacity, irrigation water should be applied before planting but not immediately after planting.

The depth of irrigation water required during the season for potatoes differs but little from that required for sugar beets under the same soil and climatic conditions. A total of 25 in. of water in ten 2.5-in. irrigations produced 266 bu per acre, almost as much as was produced with the ten 1-in. irrigations. Fifty-inches depth of water applied in ten 5-in. irrigations caused a marked decline in yield, and 10 in. applied in two 5-in. irrigations produced much less than 10 in. applied in ten 1-in. irrigations.

The results of 28 years of study of the irrigation needs of potatoes on the Utah Central Experiment Farm indicated that the yield of potatoes increases with increase of irrigation water up to about 15 in. per season and that depths of water in excess of 20 in. usually cause a decrease in yield. In a few cases, larger depths of water, although accompanied by large potato yields, seemed to be directly responsible for poor-quality potatoes.

Depth, ft	Water used	
	Inches per year	% of total
0-1	8.6	30
1-2	7.3	26
2-3	5.2	18
3-4	3.7	13
4-5	2.2	8
5-6	1.3	5

FIG. 168. Use of water from each foot of soil growing cotton in Arizona.

242. Cotton The soil and climatic conditions of many parts of the Southwest are well suited to the production of cotton. When properly irrigated and cared for cotton is a profitable crop. It has possibilities of being even more profitable with mechanical cotton pickers. As yet there has been relatively little experimental work on the irrigation of cotton.

Karl Harris and Ralph S. Hawkins worked for 6 years with differential irrigation schedules with cotton on a clay loam soil on the Mesa Experiment Farm in Arizona. The work was confined to small plots of Pima for the first 3 years and expanded to include ⅙-acre plots of both Pima and Acala.

The irrigation schedules were designed to ascertain the best type of plant growth from planting to the fruiting period to obtain maximum yields. They were also planned to test the physiological principles that growth of plants that are grown for their fruit, such as cotton, should be so regulated as to stimulate fruiting by providing for a preponderant

accumulation of carbohydrates over nitrogen and mineral plant food during the normal fruiting period.

The plants in plots receiving an early irrigation after planting were stimulated into rapid and extensive plant growth prior to heavy flowering and outyielded plots in which the first irrigation after planting was delayed until the plants started wilting.

In general, the more rapid the growth prior to heavy fruiting, the higher were the final yields. Early irrigation encouraged early fruiting. The greater percentage of the total crop was picked at the first picking of early-irrigated cotton. Plants from which water had been withheld after planting absorbed no more water from a depth of 2 to 6 ft during August, September, and October than did plants provided with an abundance of water after planting, indicating a similarity in root development.

Excessive vegetative growth during the fruiting period, even though the plants had been stimulated into rapid growth prior to fruiting, can be prevented largely by regulation of irrigation. Plants which grew most rapidly from planting to July 31 and continued growth at a moderate to low rate from July 31 to September 10 were the highest in production. Those plants which grew slowly from planting to July 31 and continued with slow growth from July 31 to September 10 were the lowest in production. Present data indicate that cotton plants should be allowed to reduce available soil moisture more completely during the fruiting period than prior to this period.

The seasonal depths of water withdrawn from the soil and the percentages of the total seasonal withdrawal of water by cotton in Arizona are shown in Fig. 168. Over half of the depth of 28.3 in. was withdrawn from the upper 2 ft of soil and only 5 percent from the sixth foot depth. Nearly one-third was withdrawn from the first foot, and the percentage of the total withdrawn decreased as the depth of soil increased.

16

Irrigation of Orchards

The irrigation of orchards is important because of the utility and the high value of orchard products. Fruit production requires large acre investments in both capital and labor, and special attention to irrigation, a practice of basic importance in the arid-region fruit-growing sections. Fruit growing has reached a high state of development in parts of California where water supplies are limited and costs are high. It is economically feasible to reduce water losses to a minimum and to attain high irrigation efficiencies. This chapter considers briefly the methods of orchard irrigation, the time of irrigating orchards, and the depths of water required by trees under certain soil and climatic conditions as found by field experiments.

243. Methods of Irrigating Orchards The furrow, the basin, and the sprinkling methods are widely used in orchard irrigation. There is an increasing interest in the irrigation of orchards by the contour check method. The sprinkling method of irrigation of orchards, shown in Fig. 169, is growing in popularity in nearly all the arid-region states, and especially in the Northwest. The method best suited to the irrigation of orchards depends on the class, type, and depth of the soil. The topographic conditions influence the method of irrigation for orchards quite as much as for irrigation of grains, forage crops, or root crops. Extreme conditions of soil permeability which result from great variability in soil texture and structure in the orchard make uniform distribution of water by the furrow method very difficult. For such conditions the basin method may be better. The cost and the degree of scarcity of water also influence the selection of method; there is no general rule universally applicable.

244. The Furrow Method An illustration of California cherry orchard irrigation by the furrow method is presented in Fig. 170. There are 7 furrows between each 2 rows of trees, thus making it easy to moisten all the soil in which the tree roots are distributed. Im-

FIG. 169. Portable pipe fixed-head circular sprinkler system for citrus orchard. (Race and Race.)

FIG. 170. Furrow irrigation of cherry orchard. (Division of Irrigation Investigations and Practice, University of California.)

portant factors to be decided in the use of the furrow method for irrigation include the furrow lengths, slopes, and spacing, all considered in Chapter 6.

245. Method of Delivering Water Important orchard-growing districts have underground-pipe distribution systems, shown in Fig. 171, with substantial savings in labor and in water. Figure 172 illustrates the design of concrete pipe. On the reader's right, the 16-in.-diameter

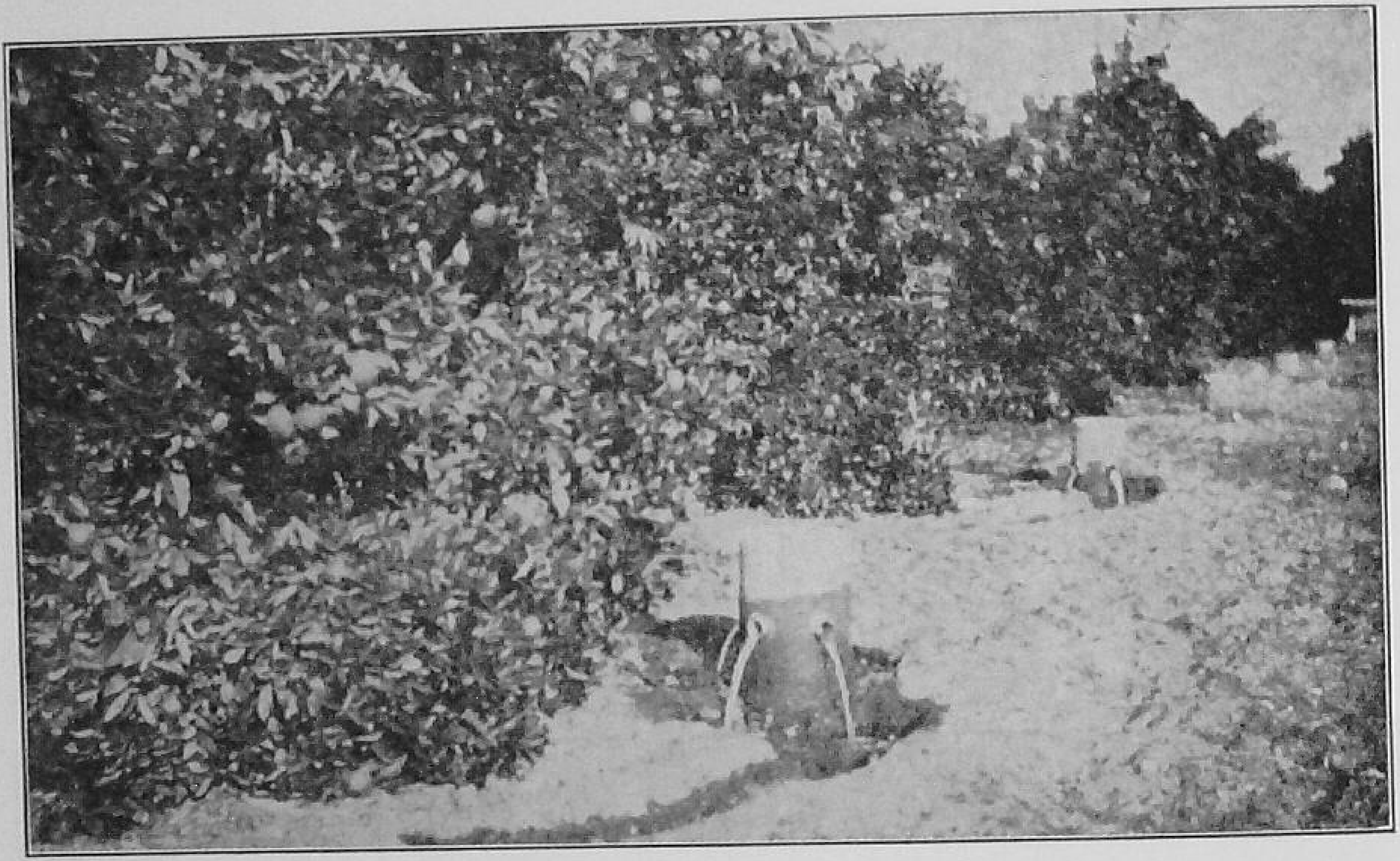

FIG. 171. Delivery of water from concrete standpipes. (*Calif. Agr. Exp. Sta. Bul.* 253.)

pressure well permits the irrigator to insert the iron cut-off gate, thus causing the water to rise in the standpipe on the left, flow through the open valve, and out of the standpipe through the four 2-in. openings. The small galvanized-iron gates at the entrance to the 2-in. outlet pipes permit convenient regulation of the stream flowing into each furrow. Some irrigators permit the water to flow from the 2-in. galvanized-iron pipes directly into the furrows. Others convey the water from the standpipe to the furrows by means of small, galvanized-iron troughs. Lightweight metal, portable surface-gated pipe facilitates control of the size of stream to each furrow, reduces soil erosion in the furrows, and increases water-application efficiencies.

246. Basin Method The basin method, as the name implies, consists of building levees midway between each row of trees in both directions so as to form a basin around each tree. A ditch is built in lateral levees in which to convey water to each pair of adjoining basins. Figure 173

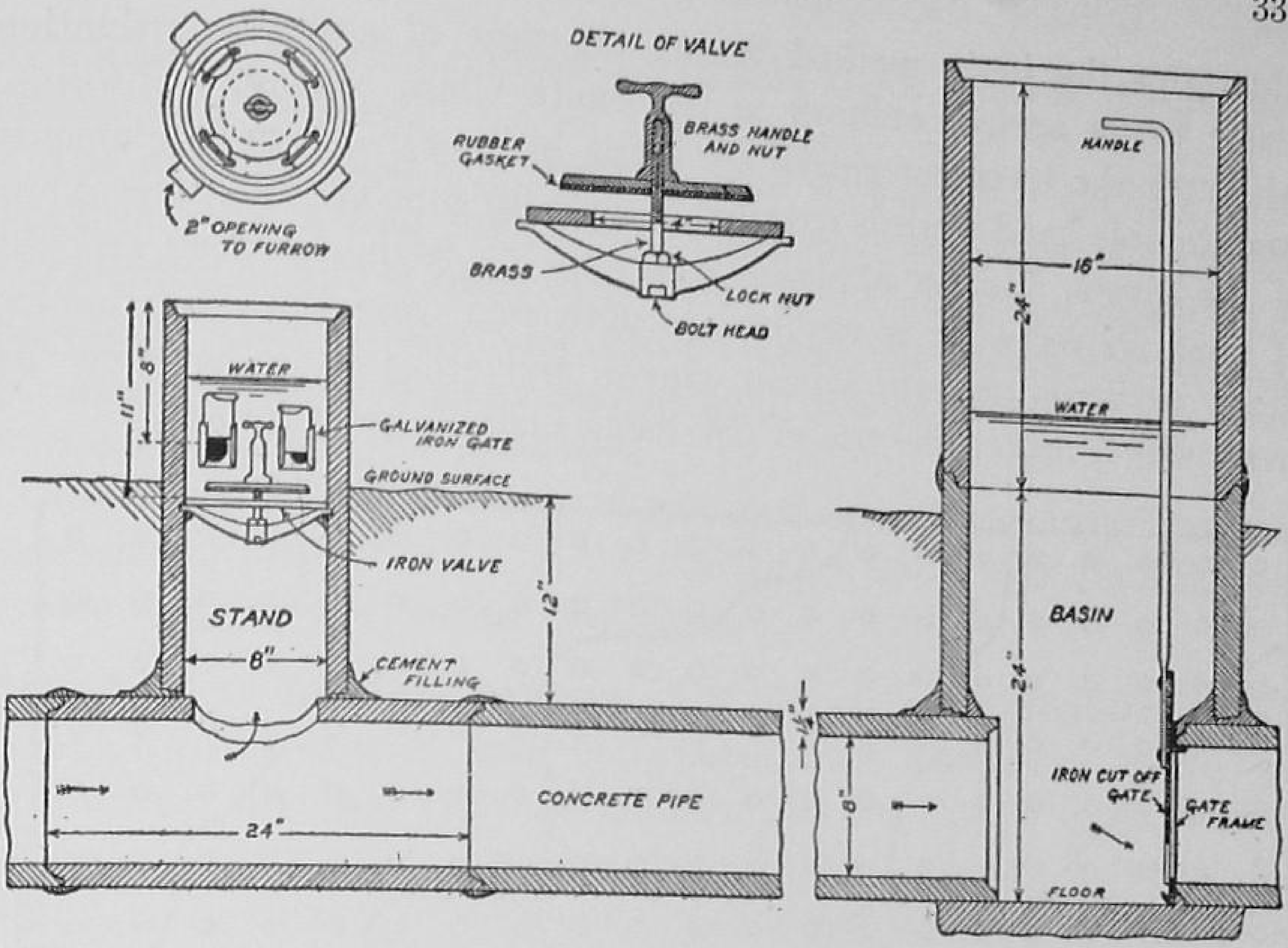

FIG. 172. Design for concrete pipe and stand system for orchard irrigation. (*U.S.D.A. Farmers' Bul.* 882.)

FIG. 173. Basin method of irrigation of apricots, Santa Clara Valley. (Division of Irrigation Investigations and Practice, University of California.)

illustrates the basin method during the time of applying irrigation water to an apricot orchard in the Santa Clara Valley, California. Although the levees or ridges are made by power-drawn implements considerable hand work is required to close up gaps at the intersections of the levees. Also in applying water to the basins a large amount of hand shovel work is required to open and close the ditch banks. Many orchards produce alfalfa, clover, and other crops between the trees, which makes the use of the basin method undesirable.

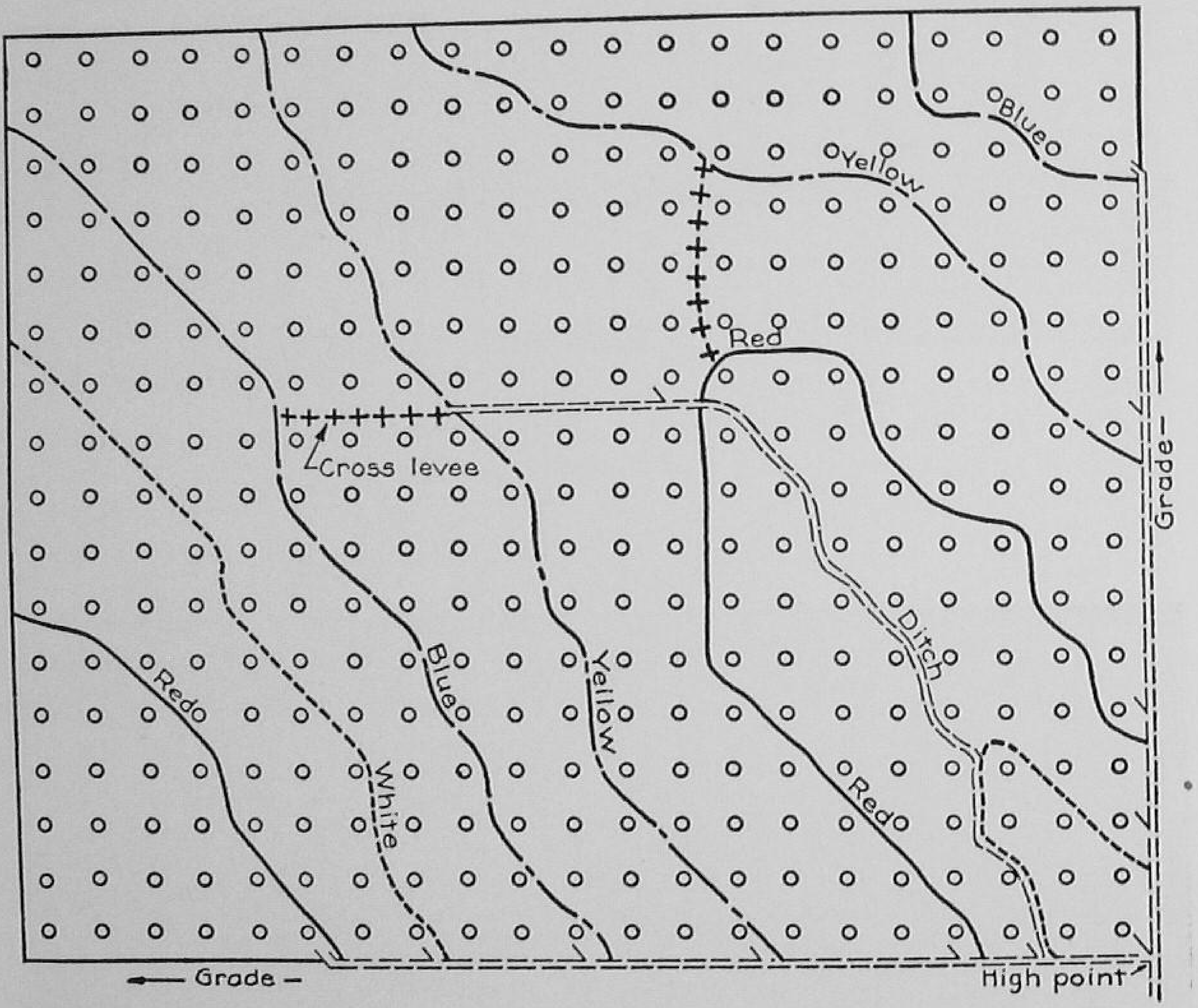

FIG. 174. Typical contour check layout for loam soils with flow of water for 900 gpm and a limit of 40 trees to a check. Order of contours in increasing elevations: red, white, blue, and yellow. (*Calif. Agr. Ext. Circ.* 73.)

247. Contour Check Method The contour check method of irrigation is not new, but its application to orchard irrigation by permanently marking contour locations on the trees by various painting schemes is a development of recent years. Contour checks are irregular basins with several trees in each basin, as illustrated in Fig. 174, formed by small levees or ridges located on contours.

The usual interval in elevation between contours is 0.2 to 0.4 ft. The contour levees are jointed at the lower boundaries of the orchard

by enclosing levees. To divide the contour check into convenient sizes cross levees are used.

The advantages of the contour check method are: (*a*) less levee work in constructing the checks is required, as compared with the rectangular checks or basin method; (*b*) less leveling and smoothing is necessary than required for furrow, basin, or rectangular checks; (*c*) larger streams of water may be used; and (*d*) less irrigation labor in applying the water is needed.

The principal disadvantage of this method is the tendency to apply excessive depths of water if the checks are large, with resulting decrease in water-application efficiencies.

248. Time to Irrigate Orchards The proper time to irrigate the different fruit trees is of great importance. Some authorities assert that fruit color, size, and yield are influenced by the time of irrigation and that the growth rate of trees is also affected. A unique feature in the study of the time of irrigation of orchards is that most trees take water from the soil continuously during summer and winter.

Dormant-season irrigation of orchards may be essential to protection of the trees, and, of equal importance, dormant-season irrigation also is practiced for the purpose of storing water in the soil. Thus the problems connected with the proper time of irrigation fall into two classes, those pertaining to irrigation during the growing season, and those which concern irrigation during the dormant season. These problems are somewhat interdependent because irrigation practice during either the growing season or the dormant season usually influences the needs during the rest of the year.

249. Irrigation During the Growing Season Trees should have moisture available at all times during the growing season. In localities of high summer rainfall caution should be exercised to avoid excessive moisture in the heavy compact soils. On the coarse-textured, porous, sandy and gravelly soils of high permeability, there is but little if any danger of excessive moisture from ordinary irrigation practice if the ground-water table is at great depth. However, shallow, coarse-textured soils have small available water capacities, and hence frequent irrigation, especially during the midseason and later, is necessary to maintain available soil water for the use of the trees.

For Elberta peach trees on gravelly loam Utah soils large depths of water applied during June and July, with no later irrigations, failed to produce marketable fruit. Moderate depths applied in eight irrigations from the middle of July to the middle of September produced satisfactory yields.

Taylor and Downing, in experiments in the irrigation of apple orchards on fine sandy loam and sandy soils in Idaho, found that the trees use larger quantities of water during midseason and late season and hence that irrigations during late July, August, and early September are of vital importance to satisfactory yields.

Irrigation of orchards during the growing season should be based primarily on soil-moisture conditions. The soil-moisture percentage changes from slightly above the point of permanent wilting up to the field capacity. The growth rate of trees and of fruit, as influenced by the moisture conditions in this range, is of vital importance. The number of irrigations per season and their frequency are therefore determined by the conditions that influence the maintenance of readily available moisture.

The available soil-moisture capacity is defined in Chapter 9 as the field capacity less the wilting-point percentage. Oregon research workers have reported many figures showing the moisture percentage of different irrigation treatments in each of the upper 3 ft of soil and also the averages of the upper 3 ft. Figure 175 is typical of the soil-moisture studies in Oregon concerning orchard irrigation. The moisture percentage in plot *E* was, as a rule, well above the wilting point. The average for the 3 ft was 20 percent of the available capacity on the "picking date," August 31.

Oregon research workers reached the conclusion that for maximum fruit production, both in size and total weight of fruit produced, it is essential to maintain the moisture percentage at not less than 50 percent of the available capacity. For the average 3-ft root-zone soil, plot *E* moisture percentage was always well above 50 percent of the available capacity, and it averaged nearly 80 percent.

Beckett, Blaney, and Taylor found in California that a crop of lemons consumed 14.7 acre-inches per acre from April 1 to October 31. During May the trees used less than 1.4 in. as compared to more than 2.5 in. during each of the months of July, August, and September. The necessary depth of irrigation water was supplied in three irrigations, two 6.4-in. applications and one 6.8-in. application. These data show remarkable uniformity in the rate of use of soil moisture between irrigations. The rate of use when the moisture percentage was approaching the lowest limit reached was substantially the same as shortly after irrigation when the soil moisture content was near the field capacity. On the basis of these experimental observations, and on many similar ones, it was concluded that, "as long as the soil moisture is above the wilting point, the moisture content has no measurable effect on the rate of moisture extraction; that is, moisture is as

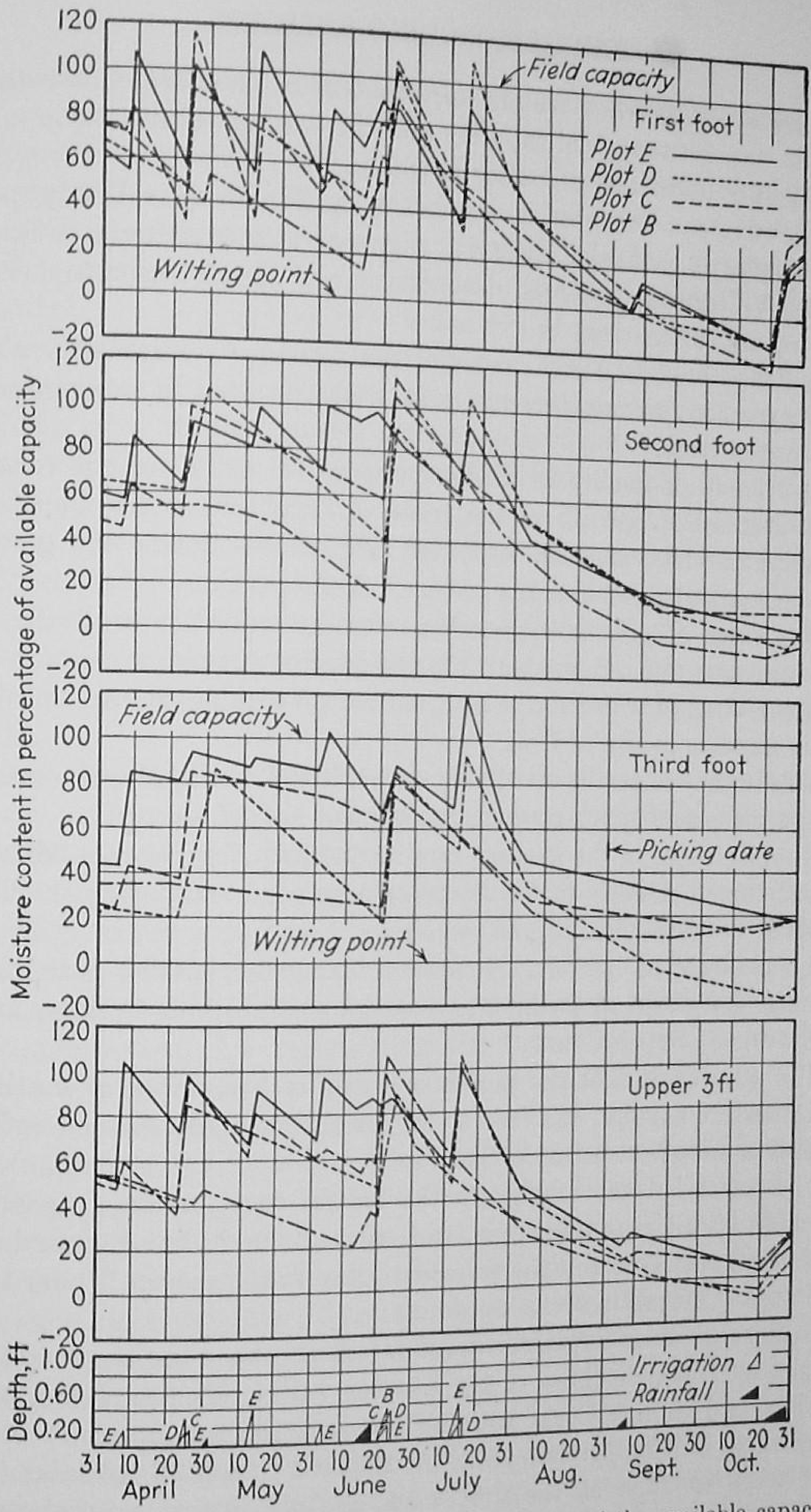

Fig. 175. Moisture content, expressed as a percentage of the available capacity, of each of the upper 3 ft and the average thereof; also rainfall and irrigation water applied, for the plots in the Klamath orchard. The heights of the triangles represent the depths of water applied by either irrigation or rainfall, and the bases show the periods of application. (*U.S.D.A. Tech. Bul.* 432.)

readily available when the moisture content is one-third or two-thirds of the way between field capacity and the wilting point as it is in the thoroughly moistened soil after irrigation."

The effects of irrigation on peaches in the San Joaquin Valley, pears and apples in central California, and prunes and walnuts in Sacramento Valley, on the basis of conclusions of Hendrickson and Veihmeyer, are summarized briefly below.

a. Peach Studies. Maintenance of soil moisture continuously above the permanent wilting percentage at Delhi resulted in production of the largest trees.

Deficiency of readily available moisture for brief periods resulted in a decrease in growth of the trees at Delhi but not a significant decrease in yield, and deficiency for long periods during the growing season markedly reduced the yields of Muir peaches.

The rates of growth of peaches were not affected until the soil moisture was reduced to about the permanent wilting percentage.

Application of water to the soil just before picking did not result in rapid increase in size of fruit.

A deficiency of readily available soil moisture during the pit-hardening period seriously affected the subsequent size of the fruit.

No differences in the keeping quality between the peaches from the wet plots and those from the dry plots were observed during the usual interval between picking and canning.

A safe interval between irrigations during the hottest part of the summer is 3 weeks at Delhi, 3 to 4 weeks in Stanislaus County, and 5 to 6 weeks in Sutter County.*

The data show that the permanent wilting percentage is a critical soil-moisture content, and lead to the conclusion that trees either have readily available moisture or have not.

b. Pear and Apple Studies. In the central coast region, in years of normal rainfall, pear and apple trees on medium- or fine-textured soils do not exhaust available moisture until late in the season. Under these conditions, irrigation seems unnecessary.

Mature pear orchards, in districts where the climatic conditions somewhat resemble those of the interior valley, such as Lake, Mendocino, and Contra Costa counties, exhaust the soil moisture to the permanent wilting percentage in the upper 4 to 6 ft of soil about the last week in June or the first week in July during normal years. Under these conditions, the trees, if growing on soil at least 6 ft deep,

* The soils at Delhi are of a light, sandy character; those in Sutter County usually heavier.

may be kept supplied with available water with one or two irrigations before harvest.

Apple experiments were conducted under mild climatic conditions. When the readily available soil moisture below the first foot is exhausted the apples slow down in growth, but when the permanent wilting percentage is not reached the growth of the fruit is not retarded.

The maturity of pears is delayed if the readily available soil moisture is exhausted a week or more before the normal harvest period.

Pears grow normally under a wide range of soil and climatic conditions when the trees are kept supplied with readily available soil moisture, but lowering of the soil moisture to about the permanent wilting percentages during the growing season causes decreased size and delayed maturity of fruit.

c. Prune and Walnut Studies. Maintenance of the soil moisture above the permanent wilting percentage for 5 yr did not materially affect the yields or quality of the prunes and walnuts in this experiment.

Excessive depths of water did not produce any visibly injurious effects in 3 yr on prune and walnut trees growing in a well-drained Yolo loam at Davis, California.

The most economical irrigation practice with prune and walnut trees has been to allow the trees to reduce the soil moisture to about the permanent wilting percentage before replenishing the supply.

In a soil permeated with roots there seems to be no physiological or economic reason for replenishing the supply of readily available moisture in prune and walnut orchards before it is exhausted.

The present status of research on orchard irrigation during the growing season indicates that, for trees, soil moisture should be readily available continuously. The necessary frequency of irrigation to maintain readily available moisture depends on the field moisture capacity of the orchard soils, the depth of water stored at each irrigation, and the rate of use by the orchards. To assure the trees readily available moisture, water should be applied before the wilting point is reached.

250. Dormant-Season Irrigation Water may be saved and waste prevented by storing it in orchard soils by dormant-season irrigation. Where orchard soils are irrigated for the purpose of storing, and thus saving, water, care should be exercised to avoid over-irrigation and consequent excessive losses of water and of readily soluble plant-food

nutrients through deep percolation. Information in Chapter 9, about the relation of available capacities to the size of irrigation stream and the hours the stream is applied to 1 acre of land, will guide the orchard irrigator in avoiding excessive application of water. The fact that water is abundant during the dormant season encourages carelessness in its application to the soil.

In orchard areas having very cold winters caution should be exercised to apply water only after the trees are fully dormant. Otherwise, dormant-season irrigation may cause late growth and winter injury associated with immaturity. The need to assure dormancy of the trees before late-fall irrigation is especially important with vigorous, growing young trees.

In Idaho, orchard soils lost approximately 2 percent of moisture during the dormant season despite 5 in. of precipitation. The soils that contained the largest percentages of moisture in the fall lost the larger amounts during the dormant season.

Basing their conclusions on the actual water needs of trees and cover crop rather than on the practice of irrigating during the dormant season to save water, Beckett, Blaney, and Taylor found that in a period of 25 yr in California there were 6 yr in which two winter irrigations were needed, 8 yr in which one irrigation was needed, and 11 yr in which winter irrigation was not necessary.

There is danger in permitting trees to go into the dormant season with a very low soil-moisture supply. A study of winter injury in Utah peach orchards led to the conclusion that lack of adequate irrigation was the most important single factor for death of trees. In a young peach orchard which received no irrigation most of the trees died the following winter, whereas an adjoining irrigated orchard recovered from winter injury.

An orchard of peach and apricot trees on sandy soil received insufficient irrigation. Trees at the lower ends of the rows received no irrigation after July 25. The upper part of the orchard was irrigated twice after that date. The trees which were inadequately irrigated did not recover, whereas those which received the later irrigations recovered fairly well; only an occasional tree and branch wilted the following summer.

251. Irrigation Water Requirements When grown without intercropping, and when kept free from weeds, orchards require less irrigation water than alfalfa, under the same climatic and soil conditions. The difference between the depths of water needed for the small grains and for orchard trees in the intermountain states is small, but the

orchards, as a rule, require late-season irrigation whereas the grains may be matured by early-season irrigation. Grains and orchards "compete" for water only during a short time near the middle of the crop-growing season. The orchards may be irrigated largely after the grains are matured. Sugar beets and potatoes require water at about the same time as it is needed by orchards. Under the same climatic and soil conditions beets and potatoes probably need slightly larger depths of irrigation water than orchards do.

252. Apples In the Rogue River Valley, Oregon, the mean annual precipitation is approximately 30 in. and during the growing season the average rainfall is 2.6 in. The irrigation-water requirements for apples range from 1000 to 3500 gal per tree per season, depending on the type of soil. The usual spacing of trees, 25 by 25 ft, makes 1000 gal per tree equivalent to a depth of nearly 9 in. Apple orchards on fine sandy loam soils in the Snake River Valley, Idaho, with a cover crop of clover, given 28.5 in. of water annually, maintained an average moisture content of 19 percent and resulted in the maximum yield and in the highest percentage of extra fancy and fancy fruit. On a sandy soil 2 to 3 ft in depth underlain by a sand of great depth near Payette, Idaho, investigators found approximately 3 ft in depth annually to give the largest fruit yields. The Payette soil also produced a cover crop of clover.

253. Pears At Medford, Oregon, the rate of growth of pears is closely related to the moisture content of the upper 3 ft of soil. Whenever the moisture content fell below 70 percent of the available capacity,* the rate of growth of the fruit was reduced. Plots having the highest soil moisture produced the largest yields and the greatest return to the grower.

For the conditions such as at Medford, Oregon, the maintenance of an available soil-moisture content of not less than 50 percent of available capacity is recommended. To be sure the soil moisture is present in readily available form, frequent examination of the subsoil with the aid of a soil auger is helpful.

The responses of pear trees to five treatments were followed through a period of 6 years, 1932–1937, the same irrigation treatment being given the same trees each year. Reduced rate of fruit growth indicated water deficits in the trees when the average soil-moisture content of the upper 3-ft root zone of soil was reduced below 50 percent of the available capacity.

The largest fruit size; the largest shoot, limb, and trunk growth;

* See Fig. 175 for example of percentages of available capacity.

the largest leaf area; and the largest average yield for the 5-yr period were produced by maintaining average soil moisture in the upper 3 ft from 50 to 75 percent of the available capacity.

If irrigation water must be conserved the least reduction in yield may be expected by delaying the application of water until about 90 days after full bloom and then during the remaining 60 days before harvest utilizing the available water in sufficiently frequent irrigations to avoid water deficits in the trees.

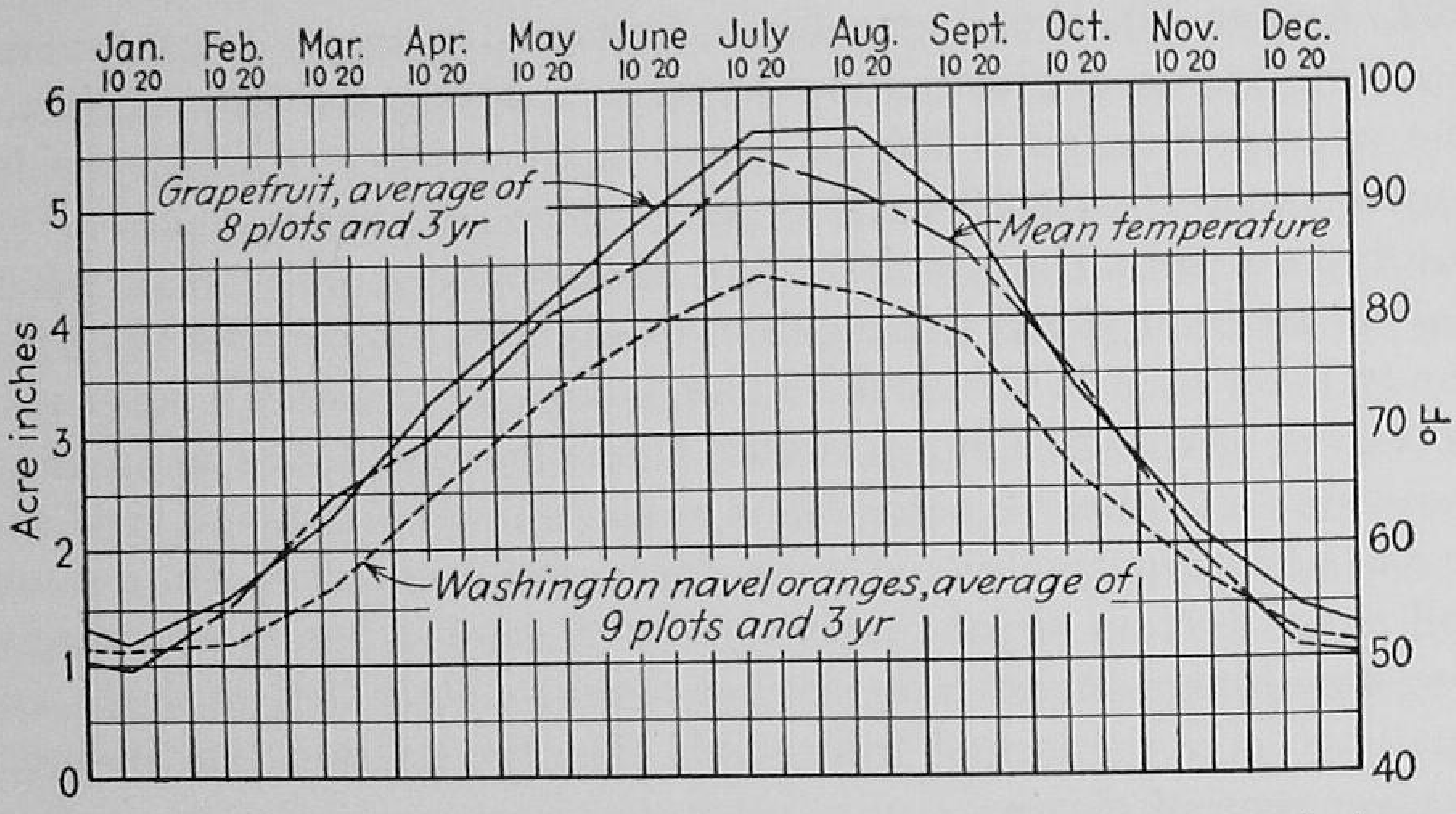

FIG. 176. Rate of use of water by orange and grapefruit trees in acre-inches per acre by 30-day intervals, and mean monthly temperatures for the period of the experiment. (*Calif. Agr. Exp. Sta. Bul.* 153.)

No injurious effect resulted from maintaining average available soil moisture between 50 and 75 percent of the available capacity for 6 consecutive years.

254. Peaches On gravelly loam soils near Brigham City, Utah, 24 in. of irrigation water produced 50 percent more marketable fruit than was produced by 47 in. Plots that were given 31 in. of water produced almost as large yields of marketable fruit as those given 62 in.

The gravelly nature of the soils prevented the use of a soil auger. Small irrigations frequently applied almost always gave better results than the same seasonal depth of water applied less frequently in larger depths at each irrigation.

255. Citrus Groves The rooting habits and irrigation requirements of citrus trees vary with the soil conditions, but citrus trees under most conditions develop relatively shallow root systems. Because of the value of the citrus crop and orchards very intensive study is being devoted to the irrigation of citrus groves.

The principal factor influencing the rate of use of water in the groves studied appears to be atmospheric temperature. Figure 176 shows that the rates of use of water are closely correlated with the mean monthly temperatures. Grapefruit utilized nearly 6 in. of water per month during late July and early August when the temperature was highest.

Harris, Kinnison, and Albert, from studies of the use of water by Washington Navel Orange trees and Marsh Grapefruit trees in Salt River Valley, Arizona, found that from 65 to 70 percent of the absorbing roots of mature citrus trees are located in the surface 2 ft of soil.

Withdrawal of soil moisture by the trees' root system was generally greatest from the first foot of soil below the surface mulch and decreased sharply with the increase in depth. Usually the extent of fluctuation below the third foot depth was slight with the soil-moisture content remaining relatively high at all times. In a majority of the groves two-thirds of the total water utilized was taken from the upper 2 ft of soil and only one-fourth from the third foot and the fourth foot together.

Harris measured the depths of water absorbed from each of the upper 6 ft of soil by navel oranges and grapefruit. The oranges absorbed 35 percent or 11.2 in. from the upper foot of soil; only 10 percent was absorbed by the oranges from the fifth and sixth foot soil sections.

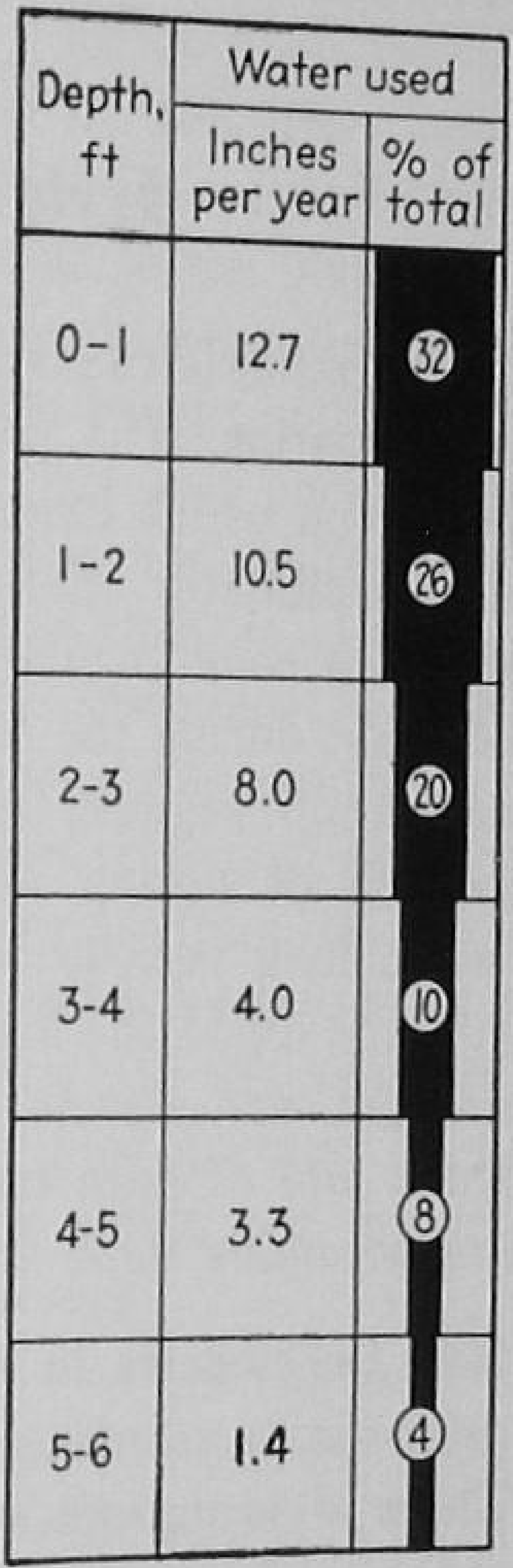

FIG. 177. Use of water by dates from each foot of the root-zone soil in Arizona.

Grapefruit obtained 57 percent of their seasonal water supply from the upper 2 ft of soil and only 11 percent from the fifth and sixth foot sections. For dates, as shown in Fig. 177, 58 percent of the season's water supply was absorbed from the upper 2 ft and 12 percent from the fifth and sixth foot soil sections. Alternate medium and light applications of water with not more than one or two heavy applications a year would take care of the water needs of these trees.

The summer irrigation requirements of mature citrus groves in San Diego County, California, range from 15 to 18 in. provided the water-application efficiency is approximately 60 percent. For trees 6 to 8 yr old, having 40 percent to 50 percent of their probable ultimate size, 6 to 8 in. of irrigation water is considered sufficient.

17
Irrigation in Humid Climates

Irrigation is fundamentally a practice of supplementing the natural precipitation. The percentage of the cultivated land of the United States on which irrigation is essential to crop production is small. In humid climates where crops are grown without irrigation the rainfall does not come regularly enough from season to season and from week to week during the season to assure profitable crop yields. The soils of humid regions, generally speaking, are shallow and therefore capable of storing only small depths of water for the use of plants. When long periods occur between rains crop growth is retarded. In order to avoid the losses due to decreased crop yields from occasional drought, and also to assure continuous and rapid growth of valuable truck and orchard crops and pasture grasses, humid-climate farmers are becoming more and more interested in irrigation.

256. Deficiencies in Rainfall One of the most interesting things in nature is its variation, its changes from time to time and place to place. There is no uniformity in nature or in the rainfall; it is continuously changing from year to year and month to month. These changes are of vital concern to agriculture in both arid and humid regions. Rainless periods of duration of 1 or more weeks during the crop-growing season frequently occur in humid-climate states. In Michigan, during a 10-yr period there were on the average 7 periods each year from 1 to 2 weeks in duration in which there was no rainfall. In Iowa, there were 8 such periods; in Wisconsin, Minnesota, Illinois, and Indiana, 6; and in Ohio, 5. A rainless period of 2 to 3 weeks' duration occurred on the average twice each year in Minnesota and once in each of the other states. Rainless periods of 3 weeks or more are comparatively rare.

The need for irrigation has been brought forcibly to the attention of farmers throughout the United States because of severe droughts that have affected much of the area. Although sufficient rainfall for the growing of ordinary crops is abundant in typical years it has been found, through costly experience, that short periods without rainfall

have ruined crops which would have brought ample returns to the farmer.

Bell has emphasized the fact that depth of rainfall recorded by the Weather Bureau does not indicate fully whether or not irrigation is needed because the character of the rain has a definite influence on the benefit secured from it. A driving rain of 1 in. or more has a high percentage of runoff and little penetration on the high land where it is needed most, whereas a gentle rain of ¼ in. or less is not enough to penetrate the soil or to be of much value to the plants. It has been found that during the growing season there is generally some period when 1 in. or more of water would be of great benefit and would have a bearing on both the quantity and quality of the crop harvested.

On the basis of a study of 30 yr of irrigation in the Willamette Valley, Oregon, where the annual rainfall is from 38 to 90 in., Powers concluded that light irrigation would be valuable insurance against drought in much of the humid and sub-humid areas of the country.

In bulletins concerning irrigation for Missouri, and regions of similar rainfall, Rubey reports that during the 77-yr period from 1870 to 1947 one-fourth of the years have been very dry and have caused excessive losses of crops. From 1870 to 1930 there were 15 dry years in which the Missouri corn crop was much below a good average. In 3 of these years it was less than half of the average yields, and during 10 of the 15 years it was less than three-fourths average.

257. Advantages of Irrigation Supplemental irrigation, as stated by Powers, (*a*) controls soil moisture and overcomes drought; (*b*) provides green pasture and green feed late in summer; (*c*) saves the clover stand and makes a cutting the first season; (*d*) makes double cropping possible (the areas that have long growing seasons produce late crops after early crops); (*e*) aids the beneficial bacterial and chemical activities in the soil; (*f*) improves quality and aids control of crop pests and diseases, especially of vegetables and berries; (*g*) increases soil moisture during the best growing weather; (*h*) aids in deep or early fall plowing and extensive cropping; (*i*) softens clods and dissolves plant food; (*j*) pays in increased yields, net profits, and productive values.

It is important that humid-climate farmers understand these and other advantages of irrigation. They should also be informed concerning the economic advisability of irrigation. They wonder about the question, "Does irrigation pay?"

Farmers in arid regions like southern California, Arizona, New Mexico, and southern Utah seldom, if ever, ask this question. They

study the probable profits in the growing of different irrigated crops, and since in these places nearly all crops must be irrigated in order to produce, or even to live, the question has no significance to them.

Some Montana farmers doubt that it pays to irrigate because they can produce reasonably good crops during some years without irrigation, and consequently some farms that could be supplied with water are operated without irrigation. Similar examples may be cited for other arid-region localities where some crops may be grown without irrigation and in which the economic advisability of irrigation is not clearly and fully established. It is a well-established fact that farmers in humid climates can assure themselves larger and more dependable crop yields, so far as influenced by available soil moisture, by providing irrigation systems and dependable adequate water supplies. But this fact does not prove that the farmers' profits will thus be increased—they may or they may not be. The humid-climate farmer should consider irrigation as a possible means of improving his economic status.

Overholt has emphasized the importance of the acre-value of the crops grown and the availability and cost of the irrigation water to Ohio farmers. In Ohio, as in other eastern states, irrigation facilities have been provided largely for vegetables, fruits, potatoes, and seed corn. Some Ohio farmers irrigate field crops and pastures.

Staebner has emphasized the fact that cost is the greater deterrent to expansion of irrigation in humid regions. In the humid-climate states, the major responsibility for determining by analysis of cost factors, and by trial, the extent to which irrigation may be economically attractive rests largely with each farm owner, or with small groups of neighbor farmers, who may develop and use water from a common source. Public agencies, concerned with the general welfare, should assist humid-climate farmers in the analyses and solution of problems of the economic advisability of irrigation.

258. Cost of Equipment and Returns Table 50 shows the cost of equipment as compared with the returns from irrigation as reported by Peikert for parts of Michigan in 1946. In the equipment cost was included the pipe, sprinklers, pump and power unit. The reports were obtained from farmers during the fall of 1946 following a season of unusually dry weather and good prices. For that reason the returns due to irrigation, as reported, are probably somewhat higher than can be expected for an average year.

Table 50 shows that as the acreage under irrigation per farm increases the cost per acre for equipment decreases. However, on the average, the added return is the largest on farms with the fewest

TABLE 50

AVERAGE COST OF IRRIGATION EQUIPMENT AS COMPARED WITH THE ADDED RETURNS FROM IRRIGATION

Range of Acreage per Farm under Irrigation	Type of Soil	Number of Farms Reporting	Total Acreage	Average Acreage Irrigated per Farm	Average Cost of Equipment		Average Added Return per Acre Due to Irrigation
					Total	Per Acre	
55–125	Sandy loam or sandy	13	1044	80	$5050	$ 63	$ 60
25–54	Sandy loam or sandy	16	600	38	3300	88	70
$2\frac{1}{2}$–24	Sandy loam or sandy	21	242	12	2000	176	122
5–125	Muck	8	289	36	1800	50	35

number of acres under irrigation. This fact is probably due to the more intense farming practices on specialized crops.

Investments of funds for irrigation facilities in humid regions, as in arid regions, are basically long-time investments. Some irrigation systems in the East have increased profits enough in the first year of operation to pay the entire cost of installation; most systems require a number of years to recover the original investment. Climatic conditions, marketing conditions, and management are among the factors that determine the rapidity with which the first cost is repaid. The crop or crops under irrigation, the depth of their rooting system, and the readiness with which they are damaged by drought or respond to irrigation are also important. Some soils show the effect of dry weather much more quickly than others. In wet years, however, a large investment is tied up in irrigation equipment without a financial reward.

Because many variables are involved it is possible usually only after a period of years to determine whether money invested in supplemental-irrigation equipment was well spent. When deciding whether it is desirable to install an irrigation system the average probable use should be carefully considered. Supplemental irrigation should be thought of as a normal farm operation. Seldom is it possible to secure and install the equipment in a short enough time to save a crop already suffering from lack of water.

259. Crops Irrigated in Humid Climates In general, irrigation in humid climates thus far is most widely practiced for the growing of small-fruit and truck crops, which bring high returns per acre and which therefore justify relatively high investments for irrigation systems. These crops as a rule are given some irrigation water every year after the irrigation systems are once prepared. Strawberries especially respond well to irrigation during the fruiting season.

Next in importance from the viewpoint of gross acre returns come the orchards of humid regions. Orchard soils may not need irrigation every year as the small-fruit and truck farms do, but the decreases in yields during relatively dry years in some humid-climate states fully justify the investments necessary to provide irrigation systems. In Virginia, for example, where the average annual precipitation is 41.6 in., or 3½ in. per mo. for the 30-yr period, 1900 to 1929, there were 10 yr in which the average monthly precipitation in July, August, and September was only 2 in. per mo. For maximum production during these important months, Virginia orchards need supplemental irrigation in amounts equal to or greater than the rainfall during the dry years.

260. Irrigation as Crop Insurance A number of experiments have been conducted in different humid-climate areas in the United States, and elsewhere, concerning the value of irrigation to insure good crop yields.

In New Jersey, blackberries, raspberries, currants, gooseberries, and other small fruits have been found to respond very well to irrigation during seasons of low and irregular rainfall. Also, in Connecticut, strawberries were early found to produce larger yields when supplied with irrigation water. Similar results were obtained in Wisconsin in a study of irrigation of potatoes, cabbage, corn, clover, strawberries, and some small grains. Early irrigation experiments in South Dakota gave marked increases in yields of several crops. In the Hawaiian Islands, under an annual rainfall of nearly 50 in., irrigation of sugar cane has been found to increase the yield.

From irrigation experiments in Michigan by the overhead-spray method Loree found that the yield of onions was increased 233 percent, beets 86, carrots 66, lettuce 60, and early cabbage approximately 100 percent. It was also apparent from these experiments that the quality of crops was improved and that more intensive cropping was possible with less cultivation than was required without irrigation.

In *United States Department of Agriculture Farmers' Bulletin* 1846 Staebner stresses the value of irrigation as insurance as follows:

> Supplemental-irrigation equipment, if available, permits a farmer to water his crops when necessary to prevent serious set-backs due to lack of moisture. It also allows the farmer to moisten his land when it is too dry to plow and thus makes possible the preparation of his land for planting at any time in the summer. Both of these conditions help to stabilize crop yields and thus emphasize the insurance quality of expenditures for supplemental irrigation. In wet years the equipment may be used little if at all, but when a drought occurs it may save a crop. Supplemental irrigation is in fact best thought of and maintained as insurance against loss of crop from drought.
>
> In the area under consideration it is estimated that of the lands with this type of insurance—supplemental-irrigation equipment—83,500 acres were devoted to the growing of truck or garden vegetables, 51,000 to orchard fruits, and nearly 200,000 to the more ordinary farm crops.

261. Sources of Water for Irrigation In the humid regions of the United States, irrigation water is obtained largely from three sources, namely: (*a*) streams, rivers, ponds, and lakes; (*b*) underground water supplies; (*c*) city water systems.

Farm pumping plants obtain water from wells and ponds, and also, to a large extent, from river systems. In humid regions large water-storage reservoirs are built to supply the domestic and industrial water

needs of great cities, but there are no reservoirs for irrigation purposes, nor are there any great irrigation weirs or canals.

Peikert found in reports from 60 Michigan farmers who practice irrigation that 36 obtained their water supply from streams, 12 from lakes, and 12 from wells. For irrigation of Missouri farms Rubey stresses the importance of farm ponds and of pumping from surface water supplies including rivers and lakes. He mentions also the possibilities, though more costly, of pumping from deep wells with the turbine pump.

For the rapid expansion of irrigation in Georgia, Davis calls attention to the importance of utilizing not only surface water supplies but also ground water from artesian basins.

Ground-water authorities in Georgia estimate that water wasted from the state's artesian aquifers equals 138 acre-feet daily. In a 4-mo. period this would amount to more than 16,000 acre-feet, enough to provide supplemental irrigation of 1-ft depth to 16,000 acres.

The essentials of an irrigation system for the eastern farmer are a water supply, a means of putting the water in motion, a means of directing its flow, and a method of distributing it so that it may be absorbed by the plant roots.

262. Methods of Irrigation in the Eastern States Several methods of applying irrigation water to soils are described in Chapter 6. The use of portable pipe for irrigation by sprinkling is shown in Fig. 178. In humid-climate states the sprinkling method is utilized to a considerable extent. For small fruits, such as strawberries, and for truck crops which bring large financial returns per acre, the sprinkling method is quite satisfactory. However, the cost of sprinkling irrigation for orchards or field crops, particularly those that are grown in rows and that can be easily irrigated by the furrow method, may be so great as to be unprofitable, whereas the costs of furrow irrigation may be fully justified by the increase in, and insurance of, crop yields. Figure 179 illustrates the furrow method of irrigation in some experimental work on the Iowa State College Farm. In irrigating asparagus, for example, the furrow method is extensively applied.

For usual Missouri conditions Rubey says that the furrow or corrugation method is best since it is less costly, requires less experience, is good for all row crops, and requires but little land leveling. He recommends furrows 220 ft long in fine sandy soils, 330 ft for loams, and 440 on clay loams; also that furrow slopes should not exceed 2 percent; and that not more than 10 gpm be used in delivery to one furrow.

The flooding method is rarely applied except for special crops such

FIG. 178. Portable pipe irrigation system in operation. (*Michigan Quart. Bul.* 29, No. 3, 1947.)

FIG. 179. Experimental irrigation plots at Iowa Agricultural Experiment Station. (Iowa Agr. Exp. Sta.)

as rice and for pastures. It is probable that the furrow and flooding methods will be extended as they are better understood. For peat soils, such as occur in certain areas near the Great Lakes, the sub-irrigation method is likely to be advantageous.

It is sometimes profitable to provide water for furrow irrigation of part of a farm and for sprinkling irrigation of other parts by installing only one pumping plant. A typical plan prepared by Williams for an 80-acre farm is presented in Fig. 180, suggesting that spray irrigation should be provided for the intensive truck plots and the strawberries, whereas the general truck crops, bush berries, and orchards should be irrigated with the furrow method. The typical humid-farm irrigation plan properly provides different methods of irrigation for different purposes. Expansion of humid-climate irrigation under plans especially adapted to the crop needs, the soil and topographic conditions, and the sources and cost of available water will tend to encourage irrigation.

263. Water Needed The depth of irrigation water needed in humid regions for any given crop depends more on the frequency of rains and the monthly depth of rainfall during the crop-growing season than it does on the annual rainfall. The irrigation water needed in humid regions therefore varies from year to year according to the crop-season rainfall. The depths of water that may be stored in the soil from a heavy rain during the crop season in humid regions is less than may be stored in the deeper root-zone soils of the arid regions from a single irrigation. In arid-region soils the approximate average increase in moisture content from a single irrigation is 6 percent. If the irrigated soil is appreciably moist before irrigation the storage capacity may be much less than 6 percent. For example, if the moisture content is increased 4 percent by 0.5-in. sprinkling irrigation, it follows from equation 35 of Chapter 9 that the depth of soil moistened is 9.6 in. provided the apparent specific gravity A_s of the soil is 1.3. When it is desired to moisten only a few inches of soil, less than 1 in. depth of water may suffice. Mitchell and Staebner advise that a sprinkling-irrigation system should be large enough and the water supply adequate to deliver at least 1-in. depth of water per week. Depths of ½ in. per application are considered sufficient for moistening seed beds and for young vegetables. For strawberries and young orchards ½ to 1 in. per irrigation is considered ample. For the seasonal needs, truckers in humid regions do not use more than 6 in., and in some seasons 4 in. will adequately supplement the rainfall.

It is important to note that the above estimates are made in connection with the sprinkling method of distribution, which permits the

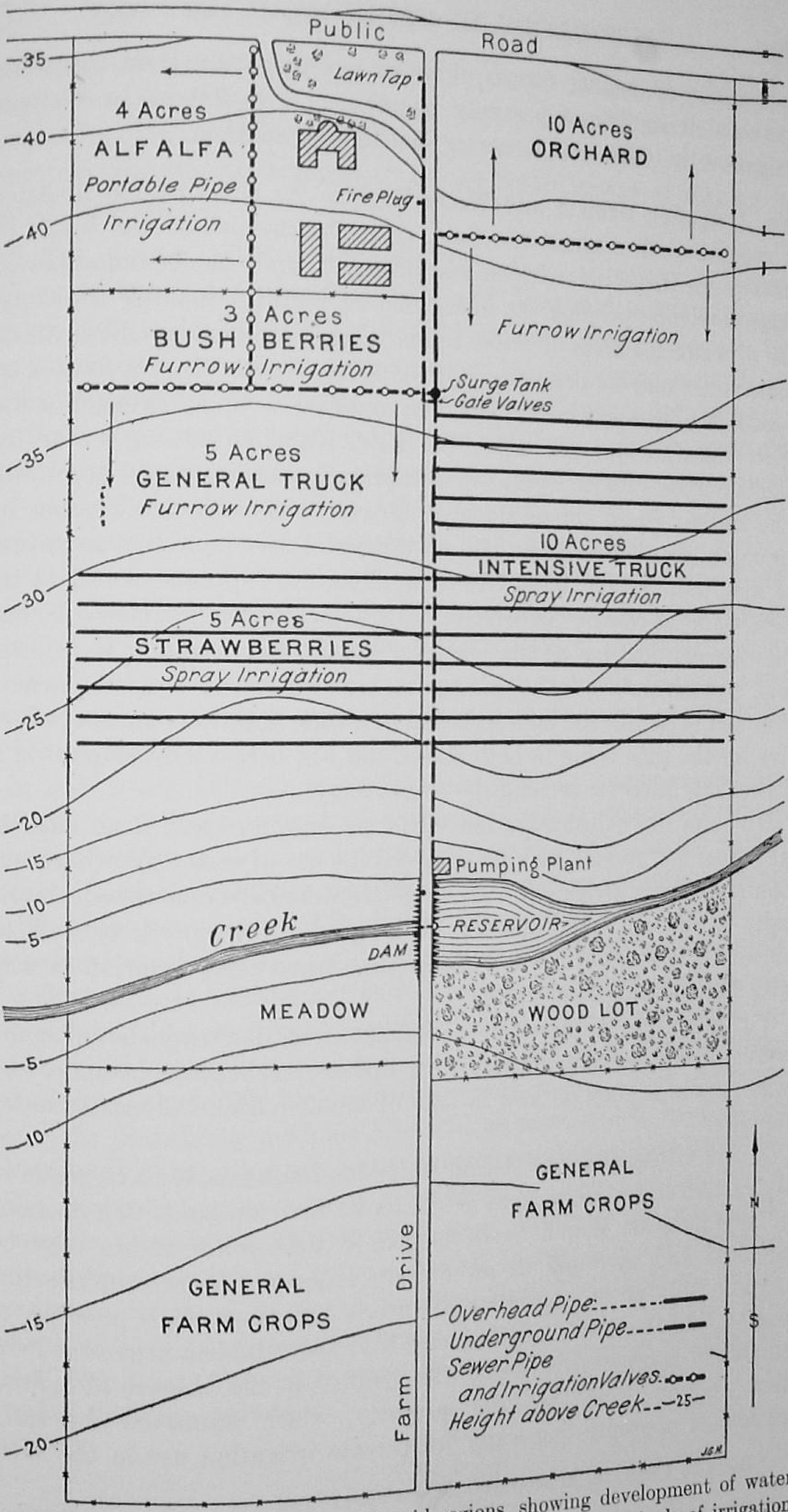

Fig. 180. Typical 80-acre farm in humid regions, showing development of water supply by reservoir and a combination of spray and surface methods of irrigation operated from one pumping plant. (*U.S.D.A. Bul.* 495.)

application of smaller depths of water per irrigation than the other methods. It is difficult to apply less than 1.5 to 2.0 in. in a single irrigation by either the furrow or the flooding method.

264. Irrigation Growth and Water Rights As the riparian doctrine is recognized throughout the East, rights to the use of the water of streams for irrigation purposes rest primarily upon the common law of riparian rights, pending the enactment of statutes making beneficial use of water the basis of water rights.* Constitutional amendments in some states may be necessary. The doctrine of prior appropriation, at least in the form in which it has been highly developed throughout the West, does not yet prevail in the East, although taking water for public purposes under legislative authorization is commonly practiced. The eastern states are as much at liberty to provide for systems of appropriative rights for any and all beneficial uses including irrigation as were those of the West. The United States Supreme Court, in its decision in the case of Connecticut *vs.* Massachusetts, declined to adopt the riparian doctrine as the basis for apportioning water. It decided that, as each state is free to change its laws governing riparian ownership and to permit the appropriation of water, the riparian law, effective for the time being in both states, did not necessarily constitute a dependable basis for settling the controversy.

Hutchins has called attention to the probability that, if an eastern state does not provide by legislation for the use of water by other than riparian owners, irrigation with stream water will be confined principally to riparian land, and that each riparian owner will be held to an equitable share of the flow at the time when other riparian owners wish likewise to use the water.

Public-service companies may establish irrigation projects under the power of eminent domain and may operate such projects under the same power as they do now in case of municipal and domestic water supplies.

If any extensive use of stream water for irrigation is to be made in the eastern states, aside from irrigation on riparian lands, the doctrine of appropriation should be developed so that water rights may be acquired and exercised in an orderly manner. To accomplish this purpose fully an appropriation statute is necessary. It is possible, of course, that the courts might decide that the establishment of a local custom of appropriating water was justified in the absence of legislation. In any event the vital necessity, which prompted the early custom of appropriating water for private irrigation use in the West

* See also Chap. 18, Articles 274–278, on water laws.

and which was later sanctioned by law, is not yet paralleled in the East. When conditions in an eastern state require the general use of stream for the irrigation of non-riparian land a carefully drawn appropriation statute appears to be the better means of making it legally possible.

265. The Future of Humid-Region Irrigation Irrigation in humid regions is likely to expand as its possibilities and advantages are more widely understood. The sprinkling-irrigation method seems to be more attractive to eastern farmers than the arid-region methods of surface application by flooding and in furrows. However, sprinkling irrigation is comparatively expensive, and high costs may tend to retard or prevent the expansion of irrigation in humid regions under some soil and crop conditions that are well suited to the less expensive surface-irrigation methods. Staebner has shown that the surface methods of furrow irrigation and of flooding which are so extensively used in the West may be adapted to eastern conditions without difficulty. It is probable that a wider dissemination of information as to the feasibility and the methods of irrigation on humid-climate farms by the ordinary surface methods will lead to expansion of irrigation in humid regions.

In any event, efficient methods of irrigation in humid regions are essential to the attainment of economical results. Especially where irrigation water is obtained by pumping against high lifts the farmer cannot afford to lose large amounts of water either by surface runoff or by deep percolation. The former losses are easily detected by inspection; the latter can be detected only by a study of the depths of soil that need moistening and the depths of water that may be retained in the soil from a single irrigation, and by regulating the depths of water applied in each irrigation accordingly. For the irrigation of crops that yield high returns per acre, such as truck and berry crops, the sprinkling methods also will be more widely used as the advantages of irrigation are better understood and facilities improved.

The very substantial progress in irrigation in a humid-climate valley of western Oregon, as reported by Powers, illustrates the possibilities in other states having high annual rainfall. In 1907 only a few hundred acres were irrigated in the Willamette Valley, which is the major agricultural valley of western Oregon, and in 1940 the irrigated area was 40,000 acres. Also, plans were then under way which promised to increase this area tenfold.

18

Social and Administrative Aspects of Irrigation

by J. Howard Maughan*

Irrigation organization and administration in this discussion is confined to two types of irrigation enterprises, namely, private and public. Private enterprises include individual projects, and mutual and commercial company organizations. The public enterprises are in two rather distinct classes:

(*a*) Those in which public laws prescribe procedure and public agencies participate in the organization and management of the enterprise without assuming direct financial responsibility, here designated as quasi-public; and

(*b*) Those organized under public laws, administered by public agencies, and financed with public funds, here designated as public irrigation enterprises.

Projects constructed under the Federal Desert Land Act and the Carey Act, together with those under the several state irrigation district acts, are considered *quasi-public;* and those financed by public agencies, whether city, state, or federal, are considered as *public projects.*

266. Individual and Partnership Enterprises Comparatively few large, but many small, irrigation projects are built by individuals working alone or as partnerships. In 1940 the Census Bureau reported that there were 86,000 such units serving 7,300,000 acres, or more than one-third of the total of 21,000,000 acres irrigated in the United States. Total investments in these enterprises were $187,000,000.

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Small streams closely adjacent to arable land in isolated sections favor individual effort in irrigation. Also, where ground water is available for pumping, or where other water sources may be best developed by small pumping plants, individuals build and operate their own irrigation projects. The advantages claimed for individual enterprises are that they permit the farmer to irrigate at any time he desires, so that he can regulate his own practices, and that he is independent of the assessments, rules, regulations, and irrigation practices of his neighbors.

Individual irrigation activity is usually more expensive than the combined activity of groups who need irrigation water, and, moreover, it is rigorously restricted by nature since it is quite impossible, as a rule, for the farmer to build the storage works, diversion weirs, and canals necessary to provide water for lands which are at great distances from the sources of water supply. The day of individual irrigation development is, therefore, in the past; the future lies with cooperation, private and public.

267. Cooperative Enterprises There are water resources and arable lands which can be brought together by small groups of individuals forming voluntarily an association for the purpose of constructing and operating irrigation systems. Cooperative irrigation enterprise is locally designated by a variety of names. All such enterprises are included in two main types of organization, incorporated and unincorporated, termed herein, respectively, mutual irrigation companies and mutual associations. In the United States, these enterprises include 4356 units, which in 1940 irrigated 6,600,000 acres, and had a combined investment in irrigation works of $224,000,000. The incorporated group units are far the more numerous and extensive.

The success of an unincorporated mutual association, sometimes designated as a mutual company, rests largely on the fairness and congeniality of each member, because the association provides no means of legally enforcing the payments of dues or of enforcing contributions to the maintenance, betterments, renewals, and operation or expansion of the project. The major asset of the association is the labor of its members. Its activities are limited to small projects which require no difficult construction and but little capital.

268. The Mutual Irrigation Company A corporate body of irrigators, voluntarily organized for the purpose of supplying water to its stockholders, is known as a mutual company. It is a non-profit organization for the delivery of water to its members only. It obtains its revenues by stock assessments, and its dividends consist of water delivered in propor-

tion to the stock owned by each irrigator. It enforces payment of assessments by the sale of stock if necessary. The stockholders delegate the responsibility of management to a board of directors, from three to seven or more, elected by ballot. Each stockholder has as many votes as he owns shares of stock. The tenure of office of directors, fixed by the articles of incorporation, ranges from one to three or more years. The directors elect one of their members as president and appoint a secretary, treasurer, and watermaster, any of whom may or may not be directors. In the small irrigation companies the watermaster has charge of the project operation and maintenance including the distribution of water to stockholders. The watermaster, with the aid of crude check gates, take-out gates, and diversion structures, is expected to distribute equitably a valuable commodity to numerous claimants.

The larger mutual companies sometimes employ an engineer-manager who is assigned the responsibility of water distribution and to whom the watermasters, one for each of several districts, are instructed to report. The mutual irrigation company has wide flexibility. It is especially suited to maintenance and operation of irrigation projects and is the dominant type of operating organization in Colorado, Utah, and southern California (aside from the Colorado River Area); it is prominent in portions of Montana, Wyoming, Idaho, and Oregon, and one phase is widespread in New Mexico.

Mutual companies are exempt from general taxation as long as they are used for the service of their own stockholders only. Some states relieve mutual irrigation companies from license taxes assessed against corporations.

269. Irrigation Districts An irrigation district is a quasi-public corporation for providing water for lands within its boundaries.

The fundamentals attributed to an irrigation district are authoritatively given by Hutchins as follows:

> It is a public corporation, a political subdivision of a State with defined geographical boundaries. It is created under authority of the State legislature through designated public officials or courts at the instance and with the consent of a designated fraction of the landowners or of the citizens, as the case may be, of the particular territory involved. Being public and political, the formation of a district is not dependent upon the consent of all persons concerned, but may be brought against the wishes of the minority. In this respect the district differs fundamentally from the voluntary mutual company and the commercial irrigation company.
>
> It is a cooperative undertaking, a self-governing institution, managed and operated by the landowners or citizens within the district. Supervision by State

officials is provided for to the extent of seeing that the laws are enforced, and in most States is extended in greater or less degree over organization, plans, and estimates prior to bond issues, and construction of works.

It may issue bonds for the construction or acquisition of irrigation works, which bonds are payable from the proceeds of assessments levied upon the land.

Hence, it has the taxing power. Each assessment becomes a lien upon the land. While the ultimate source of revenue, therefore, is the assessment, an additional source frequently provided for is the toll charged for water.

Other revenue may in some cases be obtained from the sale or rental of water or power to lands or persons outside the district.

Finally, the purpose of the irrigation district is to obtain a water supply and to distribute the water for the irrigation of lands within the district. Additional authority is granted irrigation districts, almost without exception, to provide for drainage. In some States districts may also develop electric power. These additional powers, however, are subsidiary and are intended to make more effective the principal function of the organization, which is to provide irrigation water.

During the sixty-odd years of its history the irrigation district has become an increasingly important irrigation agency. It is adapted to large-scale irrigation enterprise. Many of the larger irrigation systems of the West are managed by this type of organization. In 1940, 427 irrigation districts served 3,500,000 acres at a total investment of 266 million dollars.

270. Commercial Companies The irrigation enterprise which supplies water for compensation to irrigators who have no direct financial interest in the irrigation works, or who hold an equity which has not yet ripened into ownership and control, is designated a commercial irrigation company. This class of irrigation enterprise numbered only 225 in 1940, but their irrigated area was 1 million acres, having an investment in irrigation systems of 66 million dollars. Some commercial companies furnish water on an annual rental basis; others sell the prospective irrigator a water right and in addition charge an annual rental; and some sell a water right which carries with it a perpetual interest in the irrigation system. Commercial companies of the last type ultimately become mutual companies in which the irrigation works are owned and operated by the irrigators. Service rates of companies furnishing water on an annual rental basis are generally subject to public regulation as a result of dedication of the water to public use. The annual rentals charged by companies which sell water rights are not subject to public regulation if the contracts for sale of rights and charging of rentals are held to be private contracts.

271. Desert Land Act To encourage the irrigation of the public lands, Congress in 1877 provided that any citizen over 21 years of age may obtain title to 640 acres of desert land upon providing for its irrigation and paying a nominal fee. In 1891 the area was restricted to 320 acres. Entrymen are required to pay 25 cents an acre at the time of filing, and to make an expenditure of not less than $1.00 per acre during each of the first three years. A period of 4 yr, with a possible extension of 3 yr, is allowed in which to complete the requirements. The act is operative in all the irrigation states but Kansas, Nebraska, and Oklahoma. The only residence requirement is that the applicant must reside in the state. The act has been popular, and extensive areas of range and dry-farm lands were patented under its authority, but only limited areas were irrigated in compliance with the purposes of the law. The irrigation development is an individual matter for each entryman to work out. It is usually beyond the ability of the individual working alone to fulfill adequately. The withdrawal of public lands from entry, excepting under restricted conditions, in 1934 added difficulties to the further patenting of land under this act.

272. The Carey Act To avoid the repetition of irrigation project failures which occurred in private irrigation development during the years 1880 to 1893, Congress, in 1894, passed the Carey Act, named for Senator Joseph M. Carey of Wyoming. By the Carey Act, the Secretary of the Interior, with the approval of the President, was authorized to grant each state having desert lands an area not exceeding 1 million acres of such lands "as the state may cause to be irrigated, reclaimed, occupied, and not less than twenty acres of each one hundred and sixty-acre tract cultivated by actual settlers, within ten years after the passage of this act." In 1896 Congress authorized the state to create liens to cover construction costs and provide that patent should issue to the state when a water supply was available, without regard to settlement or cultivation, but that the United States should in no way be liable for such a lien.

In 1901 the 10-yr period was made to "run from the date of approval by the Secretary of the Interior of the State's Application for the segregation of such lands," and the Secretary was authorized to grant an extension, not exceeding 5 yr.

Twelve states, by enacting the necessary legislation, accepted the provision of the Carey Act. Reclamation has been accomplished in Colorado, Idaho, Montana, Oregon, Utah, and Wyoming, the act having been followed most extensively in Idaho and Wyoming. Projects under this act are installed as private enterprises by contractors under

agreements with the states. Requests to the Secretary of the Interior for segregation are made by a special state board, which also announces the price to be paid to the state for the land and to the contractor for a perpetual water right. Upon payment of a sufficient part of the water-right charges, the management of Carey Act projects usually passes to the irrigators, and the development company is succeeded by a mutual irrigation company.

273. United States Reclamation Projects The enactment of the Reclamation Law in 1902 was noteworthy in first providing direct use of federal funds without interest for construction of large irrigation projects.

The Bureau of Reclamation has made an outstanding contribution in the design and building of engineering structures of large magnitude.

Nearly a half-century of activity has resulted in the completion of structures as tabulated.

Construction Results. Bureau of Reclamation

To June, 1946

Storage and diversion dams	168
Reservoir capacity (acre-feet)	64,599,380
Canals, ditches and drains (miles)	18,468
Tunnels	355
Length (feet)	566,521
Canal structures	219,670
Bridges	13,902
Length (feet)	373,098
Culverts	23,816
Length (feet)	1,085,166
Pipe laid (linear feet)	12,937,155
Flumes	6,244
Length (feet)	978,492
Power plants	33
Pumping plants	335
Power developed (kilowatt-hours annually)	13,172,988,977
Telephone lines (miles)	4,010
Transmission lines (miles)	2,516
Excavation (cubic yards)	625,574,739
Rock poured (cubic yards concrete)	34,123,144
Cement used (barrels)	38,870,583

Ultimately all federal irrigation projects will be owned and operated by the irrigators as some now are. Either a mutual irrigation company or an irrigation district is created by the irrigators when they assume control; and through this organization they conduct their affairs with the government.

The salient features of projects constructed by the United States under the Reclamation Law are:

(*a*) The settler has the use of public non-interest-bearing money and a period of 40 yr in which to repay construction costs.
(*b*) Public lands for which the development of a water supply was so costly as to be in general unattractive to private capital were included in many federal projects.
(*c*) Until a substantial part of the construction charges are paid the project is under complete control of the Bureau of Reclamation.
(*d*) Annual payments of construction charges and annual operation and maintenance costs are fixed by the Bureau and paid by the settler to its representatives.
(*e*) The construction costs of multiple-purpose projects are prorated according to the benefits to irrigation, municipal water development, power development, flood control, navigation, and other purposes.

The essentials of success, as on irrigation districts and other irrigation enterprises, have proved to be productive land, sufficient water, reasonable construction costs, and adequate land settlement.

274. Elements of Water Laws Two basic doctrines, antagonistic to each other, are recognized in western water law.

The *doctrine of appropriation* asserts that all water rights are based on use; that use creates the right, and that disuse destroys or forfeits it. Beneficial use is declared "the basis, the measure, and the limit of the right."

According to the common-law *doctrine of riparian rights,* each owner along a stream is entitled to have the water flow in its natural channel undiminished in quantity and unpolluted in quality. A modified rule of the riparian doctrine was fixed by the California Supreme Court in the case of Lux *vs.* Haggin, in which the court held that the riparian right was a part and parcel of the land, neither created by use nor destroyed or suspended by disuse. The court said:

> The right in each extends to the natural and usual flow of all the water, unless where the quantity has been diminished as a consequence of the reasonable application of it by other riparian owners for purposes hereafter to be mentioned.
>
> By our law the riparian proprietors are entitled to a reasonable use of the waters of the stream for the purpose of irrigation. What is such reasonable use is a question of fact, and depends upon the circumstances appearing in each particular case.

The riparian-right doctrine has been abrogated in Utah and each of the six adjoining states and also in Montana, whereas the nine addi-

tional western states have recognized both the riparian doctrine, as modified by California, and the doctrine of appropriation. However, there is a marked tendency toward narrowing and restricting the conditions under which the riparian-right doctrine may apply in these states.

275. Legislation Concerning Water Rights The goal of water-right legislation is to provide a means by which the public may assure every holder of a water right the complete and peaceful enjoyment of such right, and thereby reduce water-right litigation to a minimum and eliminate unnecessary litigation. To accomplish these purposes it is necessary, since state control of water rights is well recognized, that each state have complete, dependable records of all existing rights. Many water rights became vested through use of water in advance of the provision of definite procedure for acquiring water rights. It is therefore essential that water-right legislation provide for: (*a*) Adjudicating rights which have become vested. These may or may not have been recorded under early laws, which provided for posting and filing notices, but not for state supervision. (*b*) Supervising and recording the acquisition of new water rights. (*c*) Distributing the waters to those who are entitled to their use.

276. Adjudication of Rights To determine or adjudicate rights to water which have become vested through use, it is essential to collect considerable field data concerning actual amounts of available water for many years during each month of the irrigation season, the net areas of land irrigated, the types of soil, and the water requirement of the different crops on the various soils, as well as date of priority. These data may be collected by each of the several water-right claimants; but, as a rule, such procedure is uneconomical and unsatisfactory because of the large number of claimants and the tendency to collect only those data that support the requests of claimants, with the result that the evidence presented to the courts is conflicting and bewildering rather than helpful toward making a fair and equitable adjudication. Some states have therefore authorized either the state engineer, or a special water-right board, to collect and analyze the necessary physical data.

Two main procedures, with variations, are followed in adjudicating water rights. In some states initiation of proceedings is in the office of the state engineer, or other designated state water authority, and may be brought on either by action of the state engineer or by water-right claimants. This procedure vests authority in the state engineer to conduct investigations and make adjudications, with the right re-

served to claimants for appeal to the courts. In other states, initiation of proceedings is in the courts by water-right claimants. Complete authority for adjudication is vested in the courts. In some states the courts are directed, or may proceed at their option, to call upon the state engineer to make investigations and propose adjudications for the use of the court.

277. Acquisition of Rights Although water rights in some states may become vested through use only, there are so many advantages to the prospective appropriator in following the procedure prescribed by the state laws that practically all rights are now initiated and perfected in accordance with these laws. Briefly, the common elements in the procedure to acquire a right to water are:

(*a*) Formal application to state engineer specifying quantity of water desired, nature and place of proposed use, point of diversion, time of use, and land areas.
(*b*) Publication of application in a newspaper having circulation in the area concerned.
(*c*) Approval of application by state engineer authorizing applicant to proceed.
(*d*) Construction of works and use of water by applicant as proposed in application.
(*e*) Filing with state engineer a formal proof of completion of works and of application of water to a beneficial use.
(*f*) Verification of proof by the state engineer and issuance of a certificate of appropriation.

If the applicant meets the requirements of the law and the regulations of the state engineer, his right dates back to the date of his application, even though several years are required to complete the appropriation.

278. Distribution of Water Complete adjudications of old vested water rights and careful public supervision of the acquisition of new rights are essential to the peaceful enjoyment of rights, but these conditions are not sufficient. It is necessary also that the several states distribute the water to those entitled to it. The responsibility of distribution is delegated by law to the state engineer or a similar officer, who appoints a water commissioner as his representative to distribute the water on each of the major stream systems. The water commissioner is given police power so that he may enforce his distribution of the stream, except as restricted by court order. The commissioner must be fully conversant with the nature, extent, and priorities of all water

rights, and well informed concerning water measurement and irrigation practices. On many streams both direct-flow and storage water rights are involved. The tasks of the commissioner are defined by the records of existing rights, but he must make many important decisions because of the variability in available water from day to day. A competent commissioner increases the economy and efficiency with which the water under his supervision is used, reduces waste to the minimum, maintains a reasonable degree of satisfaction among irrigation-company officers, and makes valuable public records of water distributed to the irrigation companies.

Appendix A

PROBLEMS AND QUESTIONS

Chapter 3

1. (*a*) Find the theoretical velocity of a jet of water flowing out of a square orifice in a large tank if the center of the orifice is 2 ft below the water surface.

(*b*) If the orifice opening considered in problem 1*a* is ½ by ½ ft, what is the theoretical discharge in cubic feet per second?

(*c*) What are the probable maximum and the probable minimum actual discharges in cubic feet per second? *Ans.* (*a*) $v = 11.33$ ft per sec; (*b*) $q = 2.84$ cfs; (*c*) $q = 2.27$, 1.7 cfs.

2. (*a*) In measuring the water that flows through a submerged orifice, is it necessary to know the vertical distance from the upstream water surface to the center of the orifice? Explain.

(*b*) Find the discharge in cubic feet per second through a rectangular standard submerged orifice 18 in. long (horizontal dimension) by 8 in. deep (vertical dimension) if the upstream surface is 7 in. vertically above the downstream water surface. First use the appropriate equation and check your result by use of a table.

3. (*a*) In using weirs with which to measure water, is it essential to make direct measurement of the velocity of the water as it flows through the weir notch? Explain.

(*b*) By means of the appropriate equation, compute the cubic feet per second over a rectangular weir having suppressed end contractions if the weir crest is 24 in. long and the water surface at a point 8 ft upstream from the weir is 5½ in. vertically above the weir crest. Check your result by a weir table.

(*c*) If the weir described in problem 3*b* has complete end contractions, would the discharge be more or less than your computed result? How much?

4. For the same length of weir crest and depth of water over crest as in problem 3*b* compute the discharge over a trapezoidal weir. Check your result with a table.

5. For a right-angle triangular notch weir, what is the discharge when the depth of water vertically above the apex of the weir notch is 0.6 ft at a point 5 ft upstream from the weir?

6. Show that doubling the effective head causing discharge through a submerged orifice increases the discharge approximately 41 percent.

7. Show that doubling the head over a rectangular or a trapezoidal weir makes the discharge 2.8 times greater.

8. Show that doubling the head over a triangular notch weir increases the discharge by 5.66 times. Does the percentage increase in discharge caused by doubling the head vary as the size of the notch increases from 60° to 100°? Explain.

9. State the basic discharge equation that is used in connection with current meter measurements. Explain briefly the rating curve.

10. Give briefly the conditions that should be provided to make a satisfactory division of an irrigation stream into unequal parts: (*a*) when the stream carries sand and fine gravel and is not measured; (*b*) when the water is clear and is measured over a weir.

11. Describe an end contraction; a bottom contraction.

12. Why should the water be made to move slowly as it approaches a weir or an orifice?

13. (*a*) A Parshall flume is to be installed to measure streams from 5 to 30 cfs. At maximum flow the depth of water in the canal is 4.0 ft. It can be increased to 5.4 ft without overflowing or endangering the canal banks. Design for economy, as well as capacity, the width of flume to use for free-flow condition.

(*b*) What is the loss in head through the flume for 25 cfs and free flow?

(*c*) What is the smallest flume that can be used if 75% submergence is allowed?

(*d*) How high above the canal bed must the crests of the flumes in parts (*a*) and (*c*) be set to allow for the loss in head?

14. Why do the cups on a current meter revolve when placed in a stream?

15. Compute the head for which the discharge over a 1-ft rectangular weir having complete end contractions is the same as that for a 90° triangular notch.

Ans. $H = 1.054$ ft.

16. By means of Tables 1, 2, 3, and 4, make a small table of the discharges over a 2-ft crest for rectangular weirs, trapezoidal weirs, and submerged orifices; the submerged orifice is to have an area of 2 sq ft. Include in the table the discharge over a 90° triangular weir for the same heads. Use heads in feet as follows: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, and 5.0.

Chapter 4

1. Consider a farm irrigation ditch in a loam soil having the following dimensions:

(*a*) Bottom width, 2.00 ft.
(*b*) Total depth, 1.75 ft.
(*c*) Side slopes of 1 horizontal to 1 vertical.
(*d*) Depth of water 1.00 ft.

Find the following properties:
(*a*) Cross-section area of stream. *Ans.* (*a*) 3.0 sq ft.
(*b*) Wetted perimeter. (*b*) 4.82 ft.
(*c*) Hydraulic radius of stream. (*c*) 0.62 ft.

2. If the bottom of the ditch described in problem 1 has a uniform slope of 5.28 ft per mile (1 ft in 1000 ft), and if the bottom and sides are kept smooth and free from weeds, what will be the mean velocity of flow and the discharge? Use $n = 0.02$.

Ans. $v = 1.7$ ft per sec.
$q = 5.1$ cfs.

3. If the canal described in problem 1 were permitted to grow weeds on the sides and bottom, what would be the velocity and discharge? Use $n = 0.04$.

Ans. $v = 0.85$ ft per sec.
$q = 2.55$ cfs.

4. For a canal of the same dimensions built in earth on a slope of 10.56 ft per mile (2.00 ft per 1000 ft), determine the velocity and discharge.

Ans. $v = 2.41$ ft per sec.
$q = 7.23$ cfs.

5. How do you account for the fact that the velocity and the discharge are not doubled when the slope is doubled?

6. For a concrete-lined ditch in good condition having the same dimensions and slope as the ditch in problem 4, determine the velocity and the discharge. Use $n = 0.014$.

Ans. $v = 3.45$ ft per sec.
$q = 10.35$ cfs.

7. If the concrete-lined ditch were built shallow and wide so that its hydraulic radius were only 0.3 ft, what would be its velocity and discharge?

Ans. $v = 2.13$ ft per sec.
$q = 6.39$ cfs.

8. If the water were conveyed through a good 2-ft-diameter wood stave pipe running full, and if the vertical drop in the water surface were 5.28 ft in ½ mile, what would be the velocity and the discharge? Neglect losses at entrance and outlet.

Ans. $v = 3.80$ ft per sec.
$q = 11.92$ cfs.

9. Define: (*a*) turbulent flow; (*b*) stream-line flow; (*c*) critical velocity.

10. Show that a square covered box flowing 0.95 full carries more water than the same box flowing full. Explain.

11. Given: a canal with 1 to 1 side slopes and cross-section area of 112 sq ft. Find the most economical dimensions.

Ans. $b = 6.48$ ft.
$d = 7.82$ ft.

12. Compute the percentage change in flow q when the coefficient of roughness n changes from 0.040 for a weedy irregular earth ditch to 0.014 for a concrete-lined canal with the same cross section. *Ans.* 286 percent.

13. Find the flow capacity of a rectangular concrete flume of slope 0.004, width 2.5 ft, flowing depth 1.6 ft. *Ans.* 21.2 cfs.

Chapter 5

1. An irrigator desires to lift a stream of 500 gpm a vertical height of 40 ft. If the loss of head in the casing and pump results in a 62 percent overall pump efficiency and the electric motor has an efficiency of 91 percent, how many kilowatts will his motor use while pumping? How many horsepower?

Ans. (*a*) Kw = 6.68.
(*b*) Hp = 8.96.

2. With the same height of lift and the same efficiencies as given in problem 1, how many kilowatts would a motor require in order to deliver a stream that would supply enough water in 30 hr to cover a 10-acre tract to a depth of 6 in.?

Ans. Kw = 12.1.
Hp = 16.25.

3. A common net water requirement for orchard irrigation is approximately 1½ acre-feet per acre. If a pumping plant (motor and pump) operates at an efficiency of 57 percent, how many kilowatt-hours energy will be required to lift water 30 ft for each acre? *Ans.* 81 kw-hr.

4. Compute the horsepower required to pump:

(*a*) A stream of 2 cfs against a head of 40 ft assuming 100 percent efficiency.

(b) Actual pump plant efficiency is 59 percent. What is the horsepower requirement?

(c) Using the schedule given in Article 63 of Chapter 5, what would the charge be per month if the motor is run continuously? Assume that voltage and term discount are received.

5. Would it be advisable to use the centrifugal pump whose characteristics are shown in Fig. 50 where it is desired that 1600 gpm be pumped against a head of 42 ft? What is the efficiency? Why is a high efficiency desirable? What horsepower would be used?

6. (a) A farmer pumps 1 cfs for 24 hr each day of the irrigation season. The static head is 20 ft, and the drawdown while pumping 1 cfs is 5 ft. If his pump plant is 60 percent efficient what does it cost him per month if he pays rates given in Article 63 of Chapter 5?

(b) If he should pump the same volume of water daily with a stream of 2 cfs for 12 hr with a drawdown of 11 ft, would it be more or less expensive? How much?

Chapter 6

1. A fruit grower is entitled to a stream of 80 Utah miner's inches for orchard irrigation. How many hours will it take him to apply 5 acre-inches per acre to an 8-acre orchard?

2. A pump owned by H has a capacity of 1100 gpm. If he spends 40 hr in irrigating a 10-acre field of alfalfa when the pump is discharging 75 percent of its capacity, how many acre-inches per acre does he apply?

3. In case you desire to apply ⅔ acre-foot per acre to a 45-acre alfalfa field in a period of 30 hr, what quantity of flow would you need? Give answer in (a) second-feet, (b) Utah miner's inches, (c) gallons per minute.

4. How many acres can be irrigated to a depth of 8 in. with a stream of 1350 gpm in a period of 19 hr?

5. In order to apply an irrigation of 9.5 acre-inches per acre per 24-hr day to a 60-acre rice field, what depth in feet would you require: (a) over a trapezoidal weir having a crest of 5 ft in length, and (b) over a rectangular weir having the same length of crest?

6. How many hours will be required to apply 4 acre-inches per acre to a 25-acre potato tract using a stream received through a standard submerged orifice which is 18 in. in length and 8 in. in width and has a coefficient of discharge of 0.61, and an effective depth of water h of ⅔ ft causing the discharge?

7. How long will it take for a 3.5-cfs stream to furnish 6 acre-inches per acre net to a 20-acre field if 10 percent of the total is lost as surface runoff? What is the average size of the runoff stream if it is running half the time?

8. Consider an alfalfa tract prepared for irrigation by the border-strip method. Assume that the soil is a loam having a permeability to water of 2 ft per 24-hr day. The border strips have a mean width of 66 ft (4 rods) and a length of 660 ft. If the irrigator turns a stream of 0.5 cfs into each strip, how far will the water advance before it is all absorbed by the soil? Hint: 160 sq rods = 1 acre.

Ans. 20 rods.

9. If a stream of 1.5 cfs is applied to a border strip 16½ ft wide (1 rod), how many hours will be required for the water to flow to each of the following distances from the head of the strip: 660, 1320, 1980, 2640 ft? Assume that the depth y

flowing over the land is 3 in. and that the infiltration rate I remains constant and is 1 in. per hr. Plot a curve showing time as abscissa and wetted area as ordinate.

Ans. 0.55 hr; 1.22 hr; 2.08 hr; 3.3 hr.

10. In problem 9 compute the average depth of water applied to the border strip during the time the water reaches each distance given.

Ans. d = 3.3 in.; 3.66 in.; 4.16 in.; 4.95 in.

11. What are the essential points of difference between the border and check methods of irrigation?

12. What is a contour? A contour interval? How would you determine the slope of land from a contour map? Illustrate with an example.

13. Upon what physical principles does equation 27 depend?

14. How would you make a field determination of y and I to be used in equation 28?

15. How would you explain the fact that when $q = IA$ in equation 28 the time becomes infinite?

16. If a 3-cfs stream is applied to a border strip of infiltration rate 0.9 acre-inch per hr and the depth flowing over the land is 2 in., solve for area covered in 1, 2, 3, 4, 5, and 6 hr by means of equation 29.

Chapter 7

1. (*a*) If the head producing flow through a submerged take-out is 0.68 ft and it is increased 41 percent, how much is q increased? (*b*) How much would the discharge increase over a rectangular weir with a corresponding increase in head?

Ans. $Q_1 = 0.843Q_2$.
$Q_1 = 0.597Q_2$.

2. (*a*) What are the essential points of difference between corrugations and furrows used for irrigation? (*b*) For a particular crop, do the soil properties influence the selection of furrows rather than corrugations?

3. (*a*) What are the major functions of diversion structures? (*b*) What forces are permanent diversion structures required to resist? (*c*) Are the dimensions of farm diversion structures, i.e., lengths, depths, and widths, influenced by the soils in which they are built? Explain.

4. (*a*) In selection of a permanent farm conveyance structure, give the conditions which would influence your choice between a flume, ditch, surface pipe, and underground pipe. Determine the size of a rectangular flume to convey a stream of 2 cfs if the slope of the land on which it is to be built is 1 ft per 1000 ft. Assume that the inside bottom width should equal twice the water depth.

5. (*a*) Why is it necessary to have a larger bottom width and depth to convey a given quantity of water through an earth ditch than through a concrete flume of the same slope? (*b*) If you were going to build an 8-in. pipe on a slope of 2 ft per mile and you wanted to get the largest possible quantity of water through it, neglecting differences in cost, what kind of pipe would you select? Why?

6. (*a*) What major objectives should influence the irrigator's selection of irrigation water distribution structures? (*b*) Does the cost of water influence the selection of a distribution structure? (*c*) Do the soil properties influence the selection of distribution structures? Explain briefly.

7. In measuring water to a farmer from a variable canal stream will a submerged orifice or a weir be most helpful toward delivery of a flow as nearly uniform as practical? Why?

Chapter 8

1. What are some of the chief agencies that influence soil-forming processes?

2. What is the chief source of the mineral compounds in soils?

3. Is it practicable for the irrigation farmer to greatly modify the texture of his soils? Why?

4. What kind of soil structure is best suited to irrigation and crop production? Describe ways in which the farmer can maintain a favorable structure in his soil.

5. Distinguish between the real and the apparent specific gravity of a soil. Is it possible for the apparent specific gravity to be equal to or larger than the real specific gravity? Explain.

6. What substances occupy the pore space of a soil? Is the percentage pore space of a field soil influenced by its water content?

7. Why is the rate of water infiltration of importance in irrigation practice?

8. For a soil of given texture and structure will a 4-ft depth of well-drained root-zone soil hold twice as much irrigation water as one of 2-ft depth? Assume that the water table is 30 ft or more below the land surface. Give reasons for your answers.

9. What properties of the soil determine the percentages of these three classes of moisture in the soil: hygroscopic, capillary, and gravitational?

10. Consider two vertical columns of soil, one a loam and one a clay, both having their lower ends in water. After having stood long enough to attain capillary equilibrium, which will have the larger moisture percentage in any horizontal plane below the maximum height of rise in the loam soil? Why?

11. (*a*) Consider three soil columns, a clay, a loam, and a sand, having one end in water. After the columns have attained capillary equilibrium, what are the probable relative heights of water in each column of the points of equal moisture content? (*b*) Account for the relative levels of moisture in the three tubes in terms of capillary tension developed by each soil.

12. Do plants wilt permanently at about the same moisture content in all soils? Why?

13. How is the moisture equivalent of a soil influenced by the texture? Why?

14. Are irrigated soils that are naturally well drained ever completely saturated? Explain.

15. Does the capillary saturation of a field soil of given texture and structure change as the plane or surface of complete saturation rises and falls? Why?

16. Classify the following five soils according to textural designations.

Soil Number	Clay, Percent	Silt, Percent	Sand, Percent	Soil Class
1	5	45	50	
2	23	77	0	
3	30	18	52	
4	45	45	10	
5	50	30	20	

Chapter 9

1. An irrigator having a flow of 150 Utah miner's inches desires to add enough water to a 10-acre orchard to increase the soil-moisture content of his soil 5 percent to a depth of 6 ft. The dry soil weighs 85 lb per cu ft. How many hours are required to apply the volume of water needed? *Ans.* 16.3 hr.

2. Find the cubic feet per second required to raise the moisture content of a sandy loam soil from 12 percent to 18 percent, dry-weight basis, on a 22-acre tract in 33 hr. Assume that dry soil weighs 80 lb per cu ft and that the depth of root-zone soil is 7 ft. *Ans.* 4.3 cfs.

3. Prove that $d = \frac{P_{ac}}{100} A_s D$.

4. To how many acres of land will a 5-cfs stream add 6 percent moisture, dry-weight basis, to the upper 5 ft of soil in 17 hr? Assume soil of an average weight. *Ans.* 17.3 acres.

5. (*a*) If 100 gm of moist soil weighs 92 gm when oven-dried, find P_w. *Ans.* 8.7%.

(*b*) If this loam soil weighs 80 lb per cu ft, oven-dried, how many pounds of moisture were present per cubic foot of soil? *Ans.* 6.95 lb.

6. What depth of water in inches was retained by the soil from a 6-in. irrigation as shown by the following moisture tests before irrigation and 24 hr after? Soil is sandy loam weighing 106 lb per cu ft when oven-dried.

Depth of Soil, Feet	Percent of Moisture Before Irrigation	24 Hr after Irrigation
1	4.89	10.08
2	5.61	8.50
3	5.35	9.35
4	4.26	7.94
5	5.19	7.64

Ans. 3.71 in.

7. Soil-moisture determinations from 20 borings in a homogeneous loam soil of a 10-acre orchard indicated an average P_w of 13.2 percent. The field capacity of the upper 6 ft of soil is 18.5 percent, and $A_s = 1.36$. Allowing 15 percent of the net volume of water applied in a single irrigation for unavoidable losses, what depth of water should the irrigator apply in order to fill the available capacity (P_{ac}) storage? *Ans.* 6.11 in.

8. If the soil of the farm described in problem 7 has a mean pore space of 53 percent, how many surface inches of water would be required to fill all the pore space in the upper 6 ft of soil after the field capacity of 18.5 percent is fully satisfied? *Ans.* 20.3 in.

9. How large a stream would be required to fill all the pore space in the upper 6 ft of the soil above described on the 10-acre farm in a period of 60 hr, allowing 15 percent of the net volume required for unavoidable water losses. *Ans.* 7.49 cfs.

10. Why is knowledge of the capacity of unsaturated soils to store water of importance in irrigation practice?

11. If an irrigation farmer knows the depth of his soil, the field capacity of each foot of soil for water, and the moisture content of the soil before irrigation, show how he can use this knowledge to determine the approximate loss by seepage after an excessively large single irrigation.

12. The soil of a certain irrigated farm is a clay loam of comparatively uniform texture to a depth of 6 ft, below which there is a coarse gravel to a great depth. Moisture determinations before irrigation and again 24 hr after irrigation show an average of 4.5 acre-inches per acre irrigation water stored in the soil from an irrigation in which the irrigator used a stream of 3 cfs continuously for 24 hr on a 10-acre tract of alfalfa. Neglecting consumptive use between completion of

irrigation and the taking of samples for moisture determinations, what was the water-application efficiency E_a? *Ans.* 62.5%.

13. The average apparent specific gravity of the soil of the tract considered in problem 12 is 1.3. Provided the mean increase in moisture content to a depth of 6 ft equals 5.35 percent, what is the application efficiency? *Ans.* $E_a = 69.5\%$.

14. Consider an irrigation project on which 35 percent of the water diverted is lost in conveyance and delivery, 25 percent of the water delivered is lost as surface runoff and deep percolation, and 30 percent of the water stored in the soil is lost by evaporation. Compute the irrigation efficiency. *Ans.* $E_i = 34.2\%$.

15. (*a*) State three major conditions that tend to make irrigation farmers satisfied with a low water-application efficiency.

(*b*) State three major conditions that tend to stimulate irrigators to attain a high water-application efficiency.

16. In a locality where the irrigation farmer can obtain plenty of irrigation water at a given price per acre, is the economical consumptive use dependent on the annual acre cost of rental, taxes, plowing, seeding, and fertilizing? Explain.

17. Enumerate the conditions, in order of their importance, which you consider most essential to the attainment of community economical use of irrigation water.

Chapter 10

1. Consider a vertical soil column of 1 sq ft cross-section area and 4 ft long. If 5 cu ft of water percolates through the column in 36 hr from a supply pipe which permits the water to flow on to the soil just fast enough to keep the soil surface covered, what is the permeability in ft per 24-hr day? *Ans.* $k = 3.33$ ft/day.

2. Measurement of the permeability of a 50-ft stratum of saturated clay soil overlying a water-bearing gravel shows that $k = 2 \times 10^{-2}$ in. per hr. If the pressure head in the gravel is 75 ft of water (measured at the lower surface of the clay) and 0 ft near the soil surface, water is flowing vertically upward through the clay. Compute the flow in cubic feet per second through a block of clay 50 ft thick and 640 acres in area. *Ans.* $q = 6.44$ cfs.

3. A contour map of water pressures overlying an artesian basin shows an average fall in pressures of 30 ft per mile. Assume a mean thickness of water-bearing gravel of 26 ft, and that $k = 2 \times 10^{-4}$ ft/sec, and compute the underground flow in cubic feet per second through a section of gravel 1000 ft long at right angles to the direction of flow. *Ans.* $q = 2.96 \times 10^{-2}$ cfs.

4. Assume that a 40-acre tract of land is irrigated frequently and given enough water to keep the soil practically saturated below the 6-ft depth but that the water table is 100 ft deep. If the average $k = \frac{1}{2}$ cfs per acre, compute the number of acre-feet of water that flows vertically downward to the water table each month. *Ans.* 1200 acre-feet.

5. Is the flow of water through soils classed as "turbulent" or "streamline" flow?

6. Considering the flow of water in canals and pipes, explain the relation of frictional forces to velocity. If the velocity of flow in canals and pipes is doubled, what is the increase in the frictional force?

7. For flow of water in soils, explain the relation of frictional forces to velocity. How do you account for the difference between the relation of frictional

forces to velocity in canals or pipes from the relation of these factors in the flow of water through soils?

8. Consider an imaginary soil column of unit cross-section area at right angles to the direction of flow of water, and state whether or not it is practicable to measure accurately the net cross-section area of the channels through which flow occurs: (*a*) for a saturated soil; (*b*) for an unsaturated soil. Give reasons for your answer.

Chapter 11

1. Explain why humid-region soils do not contain excessive amounts of alkali.

2. Provided one-half of the 831 ppm of alkali salts in lower Sevier River irrigation water were deposited in the upper 3 ft of soil each year, how many years would it take to add 0.5 percent total salts to the soil provided 2 ft of water is applied to the soil each year? Assume $A_s = 1.40$. *Ans.* 25.35 yr.

3. Is sodium carbonate a black salt? What is black alkali? What salts give rise to the occurrence of black alkali?

4. A drain tile main outlet from a 1000-acre tract discharges an average of 1 cfs during each of the 12 mo. of the year. If the average salt content of the drainage water is 1200 ppm, the irrigation water applied to the tract is practically free from salinity, and the mean depth of drains is 6 ft, what is the annual reduction in salt content of the soil in terms of the percentage of the weight of the dry soil? *Ans.* 0.0102%.

5. Explain fully why lowering of the water table is helpful toward the prevention of accumulations of soluble salts on the surface of the soil.

6. In addition to lowering of the water table, describe other means of preventing, or at least decreasing, the accumulations on the surface of the soil.

7. Under what conditions, if any, is it advisable to use, for irrigation purposes, water that contains appreciable percentages of soluble salts? What precautions are necessary to minimize the danger of using saline irrigation water?

8. Are the texture and the structure of soils related to the salinity and alkali problems? If so, explain.

Chapter 12

1. (*a*) In equation 48*a* list the quantities R, k, H, L, and h in the order of ease of measurement, placing first those that are most easily measured.

(*b*) Which of these five varies most with time? Which least?

2. Refer to Fig. 150 and equation 48*a* and explain why the flow of ground water to the drain is proportional (approximately) to the square of the effective depth of drain.

3. A new open drain is not drawing enough water from the soil to lower the water table sufficiently. To increase the drain discharge would you increase the bed slope, make the drain wider, deeper, longer, or use a combination of these remedies? Give reasons for your answer.

4. Prepare a list of advantages and disadvantages of tile drains *vs.* open drains.

5. Under what conditions, if any, can clay soils be drained efficiently by pumping? Explain.

6. Determine the flow from the soil into a 10-ft-depth open drain 400 ft long when the drains are spaced 150 ft apart. The depth of pervious stratum is 15 ft, and the depth of the water table midway between drains is 3 ft below the

ground surface. The average permeability of the pervious stratum is 4.5×10^{-4} fps. *Ans.* $Q = 0.29$cfs.

7. For a soil of great depth and uniform permeability, with all other conditions as in problem 6, determine the flow into the tile drain by means of equation 49. *Ans.* 0.66 cfs.

8. In problem 6, what will be the change in flow q, toward the drain, if all other factors remain unchanged, but: (*a*) The spacing of the drain lines S is doubled. (*b*) The permeability of soil k is doubled. (*c*) The depth of the drain is increased from 10 to 12 ft.

9. Sandy loam soil, to be drained, is 50 ft deep and has a permeability of 1×10^{-4} fps. The water table is 4 ft below the ground surface. Seven-foot-depth tile drains 500 ft long have a slope of 1/2000. Determine the discharge of each drain and the spacing for 6-in.-diameter tile flowing half full. Assume the flow toward the drain is through semicylindrical surfaces. *Ans.* $q = 0.075$ cfs. $S = 270$ ft.

10. In a field drainage experiment by pumping from an artesian aquifer the following data were obtained:

(*a*) Flow of water to well or pump discharge	$Q =$	4.2 cfs
(*b*) Radius at maximum pressure head	$R =$	1480 ft
(*c*) Radius at minimum pressure head	$r =$	18 ft
(*d*) Pressure head at maximum radius	$H =$	26 ft
(*e*) Pressure head at minimum radius	$h =$	7 ft
(*f*) Depth of water-bearing aquifer	$D =$	16 ft

Find the permeability in feet per second.

Chapter 13

1. A farmer owning "bench" land in which the sandy loam soil averages about 4 ft deep and is underlain by gravel and coarse sand to a depth of 30 ft or more discovered in March by borings with a soil auger that the light winter precipitation had penetrated the soil only to a depth of 6 in. He at once applied a 5-cfs stream of flood water to his 20-acre tract and kept the stream well spread out on the land for a period of four 24-hr days in order to give the soil a good soaking. Find approximately what percentage of the water applied was lost by deep percolations. There was no surface runoff. *Ans.* 65.6 to 78.5%.

2. What are the major purposes of irrigating soils during the non-growing or dormant season?

3. Is the growth rate of crops seriously retarded as soon as the moisture content falls below the optimum moisture percentage? Explain.

4. Explain why clay soils retain larger percentages of unavailable water than sandy soils do.

5. Under what conditions, if any, is it justifiable to divert water from partly filled storage reservoirs during the non-growing or dormant season for irrigation purposes?

Chapter 14

1. If the transpiration ratio of alfalfa is 850, and field-cured alfalfa contains 8 percent water, how many acre-inches of water are transpired in order to produce a 4.5-ton crop of alfalfa per acre? *Ans.* 31 acre-inches.

2. Consider a sugar-beet field in which moisture tests in the upper 5 ft of soil

at the beginning of the season show respectively 5.6, 4.7, 3.8, 2.2, and 0 percentages of moisture greater than at the end of the season. The crop-season rainfall was 2 in., and a depth of 16 in. of irrigation water was applied. The average apparent specific gravity of the soil is 1.35; the average yield of sugar beets is 17 tons per acre, of which 18 percent is dry matter. Assume that there was no deep percolation water loss, and compute the evapo-transpiration ratio.

3. Under what conditions, if any, is the magnitude of the evapo-transpiration ratio less than the transpiration ratio? Equal to it? Greater than it?

4. Under what conditions, if any, might the making of a soil mulch by cultivation fail to conserve water?

5. What is the distinction between the evapo-transpiration ratio and the consumptive use in its basic sense as defined herein?

6. Are studies concerning the consumptive use of water in irrigation likely to increase in importance as time advances? Why?

7. What do you consider the most difficult factors to control in determining the consumptive use U by experiment on field plots?

8. Find a graph showing the average mean daily temperature in your locality and compute the seasonal heat available to alfalfa in day-degrees. Specify assumptions you consider necessary to this computation.

Chapter 18

1. State the essential differences between quasi-public and public irrigation organizations.

2. What are the essential differences between mutual associations and mutual irrigation corporations? Can a mutual irrigation corporation sell the land owned by its delinquent stockholders in order to collect payments of irrigation assessments?

3. Why has the commercial irrigation corporation been less influential than the mutual irrigation corporation?

4. Does the federal government advance funds with which to build irrigation works on Carey Act projects?

5. Can an irrigation district sell the land owned by its delinquent members in order to collect payments of irrigation assessments?

6. What form of public irrigation enterprise preceded the creation of the United States Reclamation projects?

7. In western water law, what are the distinguishing features between the doctrine of appropriation and the riparian-rights doctrine?

8. What basic elements are essential to completeness of legislation concerning water rights?

9. Describe briefly the important procedure in the adjudication of water rights.

10. What are the several elements requisite to the acquirement of new water rights?

Appendix B

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